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SARAH, A Surface Water Assessment Model for Back Calculating Reductions in Abiotic Hazardous Wastes

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SARAH is an interactive, menu-driven computer program with three default data sets that can be rapidly modified. The analytical solutions for contaminant behavior in the catchment and stream near the facility allow rapid, multiple calculations needed for good sensitivity analysis. SARAH is a modular FORTRAN program that can be modified and expanded with ease. The first version is written for a VAX 11/785 minicomputer. A subsequent version will operate on personal computers.

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ATHENS, GA 30613

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FOREWORD

As environmental controls become more costly to implement and the penalties of judgment errors become more severe, environmental quality management requires more efficient management tools based on greater knowledge of the environmental phenomena to be managed. As part of this Laboratory's research on the occurrence, movement, transformation, impact, and control of environmental contaminants, the Assessment Branch develops state-of-the-art mathematical models for use in water quality evaluation and management.

The calculational framework and many of the equations incorporated into this model were originally developed for EPA's Office of Solid Waste (OSW) in support of the Land Disposal Banning Rule. These have been updated in response to public comment, private peer review, and continuing improvements in environmental science. Additional equations have been added to address toxicant disposal through wastewater treatment facilities. The resulting Surface water Assessment model for back calculating Reductions in Abiotic Hazardous wastes (SARAH) is not meant to represent OSW policy on analysis of land disposal facilities. Rather, it is intended to provide analysts the means to rapidly explore the consequences of a variety of exposure and effects scenarios resulting from disposal of toxicants. Appropriate application of the model will provide valuable information on which to base pollution management decisions by various industrial, state, and Federal organizations.

Rosemarie C. Russo, Ph.D.
Director
Environmental Research Laboratory
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ABSTRACT

The nearfield surface model (SARAH) calculates maximum allowable hazardous waste concentrations based upon predicted exposure to humans or aquatic life from contaminated surface water. The surface water contamination pathways analyzed in SARAH include groundwater leachate from a land disposal facility, storm runoff from a land disposal facility, and discharge through a waste water treatment facility. The human exposure pathways considered include ingestion of treated drinking water and consumption of contaminated fish. Acceptable leachate or industrial waste contaminant concentrations are predicted by a "back calculation" procedure from chemical safety criteria in surface water, drinking water, or fish.

SARAH is an interactive, menu-driven computer program with three default data sets that can be rapidly modified. The analytical solutions for contaminant behavior in the catchment and stream near the facility allow rapid, multiple calculations needed for good sensitivity analysis. SARAH is a modular FORTRAN program that can be modified and expanded with ease. The first version is written for a VAX 11/785 minicomputer. A subsequent version will operate on personal computers.

This report covers a period from January 1985 to September 1986, and work was completed as of September 1986.

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The nearfield exposure model described in this manual was developed for EPA's Office of Solid Waste in support of the Land Disposal Banning Rule, published in the January 14, 1986, Federal Register. This manual is based upon the background report "A Methodology for Assessing Surface Water Contamination Due to Land Disposal," and we gratefully acknowledge the contributions of two of the co-authors--Lee A. Mulkey and Peter S. Huyakorn. The overall scope and technical approach was significantly influenced by Mr. Mulkey. Original drafts of the background report were reorganized and enhanced technically by Dr. Huyakorn. We also acknowledge the patient efforts of the OSW project officer Eydie Pines. Ms. Pines coordinated the technical and policy reviews of the original analysis, prepared summaries for the Federal Register, and supervised the modification and application of the methodology.

Ronnie Moon, of Computer Sciences Corporation, created the original computer program and updated it to keep track of changes in the methodology. Michael J. Ungs, with Tetra Tech, thoroughly reviewed both code and documentation, and programmed the enhancements suggested by Dr. Huyakorn. Gerhard Jirka reviewed the documentation and offered a valuable critique. Many others provided criticism and suggestions in public comment to the proposed rule in the Federal Register. Annie J. Smith was responsible for the typing and final preparation of the manuscript. Her efforts continue to earn our respect and appreciation.

SECTION 1

INTRODUCTION

Industrial wastes containing potentially hazardous compounds are often disposed of through wastewater treatment facilities or land disposal sites. Contamination of surface water and exposure of humans and aquatic life to hazardous compounds can occur from industrial wastes discharged from wastewater treatment facilities or leaked from land disposal sites. If expected exposure levels are too high, industrial wastes must be pretreated to an acceptable level before introduction to treatment plants or disposal sites. To help the analyst establish minimum pretreatment levels, the surface water assessment model (SARAH) was developed to "back calculate" appropriate pretreatment concentrations from chemical safety criteria for exposure to humans and aquatic life. SARAH should allow the user to screen a list of chemicals and identify those that should be restricted or more fully treated before discharge from an industrial plant.

The first step in this kind of analysis is to describe a set of scenarios that might lead to the undesired consequences. As illustrated in Figure 1, the three loading routes to surface water considered in SARAH are direct discharge in municipal and industrial wastewater effluent, overland runoff from a land disposal site, and leaching to ground water from a land disposal site. Once in surface water, chemicals are advected, dispersed, and degraded by several mechanisms, reducing their concentrations. These aqueous concentrations may result in exposure to aquatic life and to humans through drinking water or consumption of fish. Figure 2 outlines the contamination scenarios considered in SARAH.

The second step is to assign probabilities to each scenario. It is virtually certain that aqueous chemicals introduced at a wastewater treatment facility will be discharged in the effluent. On the other hand, the probability that chemical solids introduced to some land disposal sites will escape through runoff or leaching can be very small. Design and operating requirements for land disposal facilities promulgated under Parts 264 and 265 of the Resource Conservation and Recovery Act (RCRA), for example, include liners, leachate collection and removal systems, ground water monitoring, corrective actions, and run-on and runoff controls. Nevertheless, this exposure model assumes failure of all controls, leading to surface water contamination from both a ground water and a surface runoff route. Thus, SARAH sets the probability of occurrence of various scenarios to 1.0 and helps the analyst investigate the consequences.

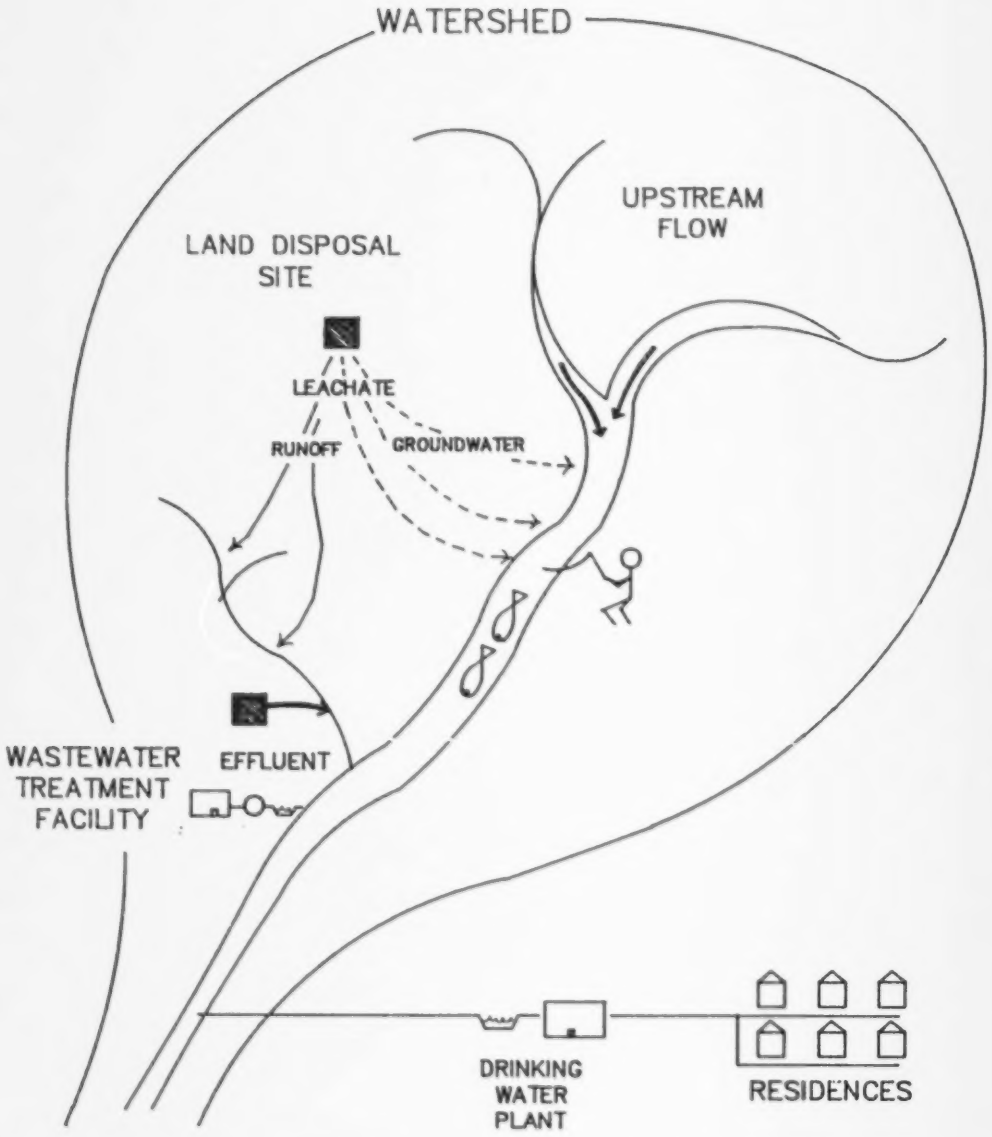


Figure 1. Routes of exposure to hazardous chemicals in surface water.

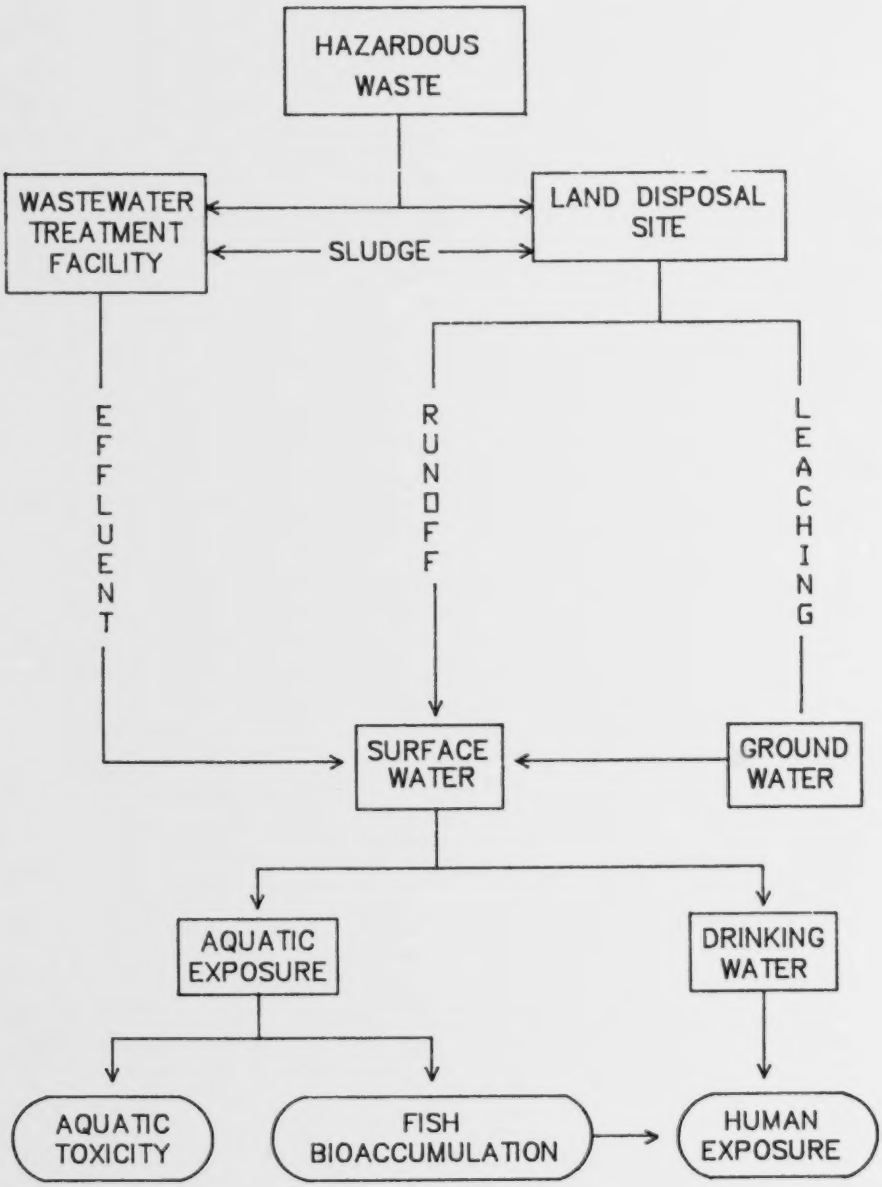


Figure 2. Routes of exposure to hazardous chemicals in surface water.

The third step is to investigate the consequences of each scenario. Aquatic and human exposure to hazardous chemicals at high enough concentrations can result in such undesired consequences as chronic toxicity in aquatic organisms and cancer in humans. This analysis begins with criteria set to protect against such adverse effects. A stream concentration criterion is designated to protect aquatic life resident in the stream. Dose criteria set to protect humans must be translated to drinking water and fish concentrations assuming specified patterns of water and fish consumption. SARAH begins its back calculations with these resulting "safe" concentrations and assumes that lower concentrations produce no adverse effects.

SARAH includes five scenarios for the contamination of surface water: (1) leaching and subsequent delivery of contaminated ground water to streams; (2) steady runoff from a once-in-25-year, 24-hour storm event averaged over a 24-hour period; (3) pulse runoff from a once-in-25-year, 24-hour storm event that is stored for a 24-hour period and released over a short time period into a receding stream flow; (4) steady loading through a wastewater effluent, and (5) pulse loading through a wastewater effluent. For each contamination route, SARAH can consider up to three potential adverse effects: (a) human exposure through consumption of contaminated drinking water, (b) human exposure through consumption of contaminated fish, and (c) direct toxicity to the aquatic community. Unrealistic combinations of contaminant release and adverse effects are not implemented in SARAH, as discussed below.

This manual contains three main sections that can be used independently. The first, Theoretical Basis of Model, documents the equations and assumptions underlying the model components. This section describes the procedures developed for evaluating the influence of wastewater discharge or land disposal on both health-based and environmental impacts. The overall approach is based on a "back-calculation" to identify acceptable wastewater or leachate concentrations given health-based or environmental thresholds that are not to be exceeded at specified exposure points (or routes). This section characterizes potential pathways leading to human and environmental exposure, evaluates the likelihood of exposure for each pathway, and sets up backcalculation procedures for those pathways and exposure routes that are likely.

The next section, User's Manual, explains the model menus, documents the generation of input data, describes the scenario variables, and lists the default values. The final section, Programmer's Manual, documents the hardware and software requirements necessary to support SARAH. Specifications for the installation and implementation of SARAH are given and a description of the computer program, which includes an overview of input/output units, the COMMON block and subroutines, is provided.

In developing the equations, four main symbols are used:

$\dot{m}$ = chemical mass flux, in grams per second

Q = volumetric flow rate, in cubic meters per second

C = chemical concentration, in milligrams per liter (equivalently, grams per cubic meter)

ζ = multiplication factor, representing attenuation or enhancement of mass flux or concentration, unitless

Subscripts are used to distinguish the various fluxes, flows, concentrations, and multiplication factors. Among the most common are:

L = leachate from solid waste disposal facility

W = industrial waste stream

g = groundwater in catchment contaminated by solid waste disposal facility

D = wastewater effluent discharged to stream

R = surface runoff

U = upstream

O = instream at downstream edge of initial mixing

y = lateral distance across stream

x = longitudinal distance downstream

DW = drinking water

F = fish uptake

EXP = aquatic exposure

ADI = acceptable daily intake of water by humans

ADI' = acceptable daily consumption of fish by humans

SECTION 2

THEORETICAL BASIS OF MODEL

The fundamental principle underlying this model is mass conservation. The equations solved by SARAH describe mass fluxes of chemicals in leachate, effluent, runoff, and stream. Often, however, stream standards and waste requirements are specified in terms of concentrations. For each step, mass flux equations are developed and then presented as a series of concentration reductions (or enhancements) between the waste release and the point of exposure. The reduction factors are later considered in detail.

In this section, the potential pathways leading to contamination of surface water and exposure to aquatic organisms and humans are explored. Next, a set of exposure scenarios resulting from the pathways is considered. Finally, the actual equations describing the mass transport, dilution, and transformation processes are developed.

2.1 POTENTIAL EXPOSURE PATHWAYS

Pathways leading to contamination of surface water and exposure to aquatic organisms and humans begin with the disposal of industrial wastes in wastewater treatment or land disposal facilities. Wastewater effluent or land disposal leachate can enter a stream through ground water transport, surface runoff, or direct discharge. Contaminants in stream are subject to advection, lateral and longitudinal mixing, and physical, chemical, and biological reactions. Aquatic organisms are exposed directly to instream concentrations. Human exposure occurs through consumption of contaminated fish or drinking water that has been processed through water treatment plants located downstream of the discharge. These sequential pathways are explored in the following sections.

2.1.1 Contaminant Loading to the Stream--

Contaminant leaching and transport in ground water system--The release and transport of hazardous constituents from a landfill through the ground water pathway of the model assumes that the land disposal unit is hydraulically connected to a stream (Figure 3). When liners or leachate collectors at the base of the land disposal unit fail, leachate enters the aquifer directly below the land disposal unit. Precipitation of metals is assumed to occur at this point, placing upper limits on their dissolved concentrations. Dissolved chemicals are then transported through the aquifer under the com-

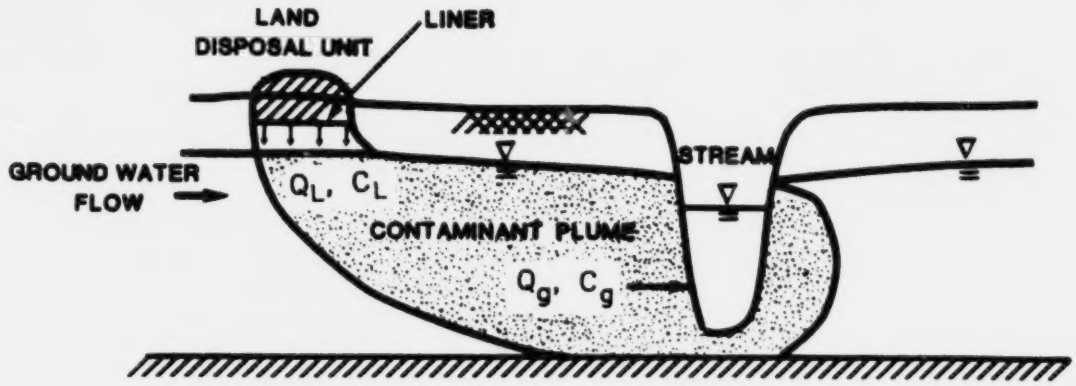


Figure 3. Contaminant tracking and transport in ground water system.

bined influences of advection and hydrodynamic dispersion as well as sorption and biochemical degradation for nonconservative species. The contaminants discharge into the surface water throughout the zone where the aquifer and the stream intercept.

The mass flux at the ground water interception zone or surface water entry area, $\dot{m}_g$, and the mass flux of leachate, m_L, may be related by:

$$\dot{m}_g = \zeta_H \cdot \dot{m}_L \tag{1}$$

where the mass flux units are expressed in grams per second, and ζ_H is a ground water attenuation factor accounting for the effects of hydrolysis in the aquifer. The average concentrations at the ground water interception zone and in the leachate can be obtained by dividing the mass fluxes by the flow rates:

$$\overline{C}_g = \dot{m}_g/Q_g \tag{2}$$

$$C_L = \dot{m}_L/Q_L \tag{3}$$

where flow units are expressed in cubic meters per second, concentration units are expressed in milligrams per liter, and subscripts g and L refer to ground water and leachate, respectively. Combining the above equations, the average concentration at the ground water interception zone and the leachate concentration may be related by:

$$\overline{C}_g = \zeta_g \cdot C_L \tag{4}$$

where ζ_g is the ground water reduction factor:

$$\zeta_g = \zeta_H \cdot Q_L/Q_g \tag{5}$$

Methods for calculating these parameters are developed in later sections.

Surface runoff from land disposal units--All RCRA Subtitle C land disposal units (landfills, land treatment facilities, waste piles, and surface impoundments) must be designed such that, at a minimum, runoff from a once-in-25-years, 24-hour storm event is contained (40 CFR Parts 264 and 265). Precipitation events of greater magnitude than the 25-year, 24-hour storm event are assumed to occur at a sufficiently low probability that the protective design can be considered to provide an acceptable level of performance. Other land disposal systems (RCRA Subtitle D) may be designed to contain lesser storm events. "Failure" of a land disposal system, illustrated in Figure 4, refers to its inability to contain a design storm event. Direct surface runoff of leachate plus solids from surface impoundments is assumed to occur from the "failed" containment unit over a time period t_R.

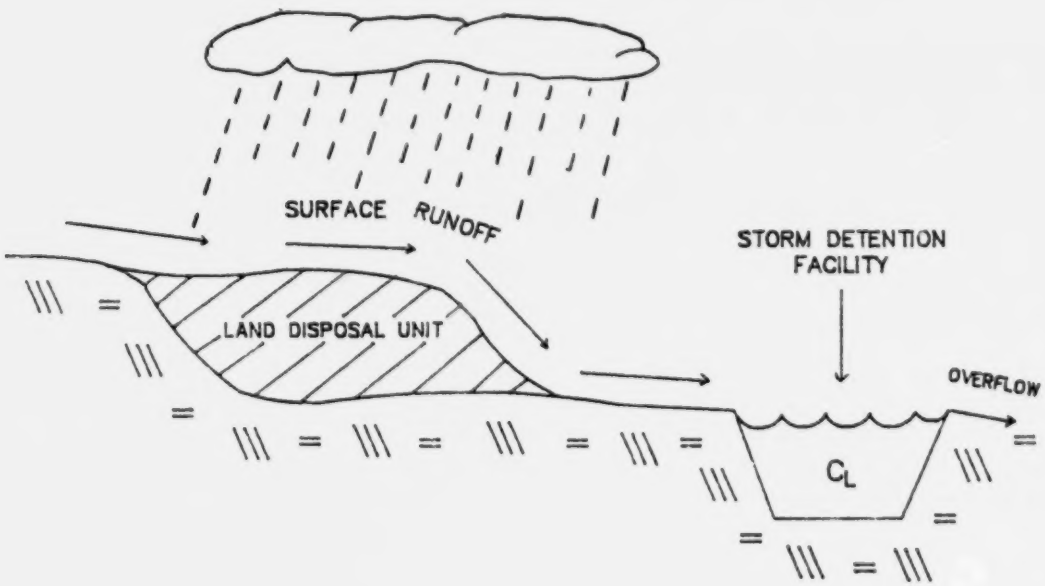


Figure 4. Surface runoff from land disposal units.

The concentration in the runoff leaving the containment facility is assumed to be equal to the leachate concentration, C_L. This assumption is somewhat conservative: for the case involving surface impoundments, the runoff concentration may be slightly reduced due to dilution from precipitation water that fills the freeboard depth; for the case of landfills and waste piles, not all the precipitation will have contact with the waste and hence will be at a lower concentration.

Two types of surface runoff are considered. The first assumes containment failure that allows leachate from storm runoff to enter a stream steadily throughout the duration of the 24-hour storm. The second assumes sudden containment failure that allows leachate generated during an entire storm event to enter the stream as a pulse at the end of the storm. The time over which the steady loading occurs is assumed to be equal to 24-hours (the duration of the storm). The duration of the pulse loading is assumed to be between 10^3 and 10^4 seconds (approximately 15 minutes to 3 hours).

Because runoff leaving the containment facility is assumed to be at the leachate concentration C_L, the runoff mass flux $\dot{m}_R$ is equal to:

$$\dot{m}_R = C_L \cdot Q_R \tag{6}$$

where Q_R is the runoff flow rate, in cubic meters per second. The mass flux in runoff entering the stream is assumed equal to that running off the facility, because the short travel times should not allow transformation reactions to occur significantly. Concentrations in the runoff leaving the land disposal facility and entering the stream can be obtained by dividing the mass fluxes by the respective flow rates:

$$C_R = \dot{m}_R/Q_R \tag{7}$$

$$C_{SR} = \dot{m}_R/Q_{SR} \tag{8}$$

where Q_{SR} is the runoff flow to the stream from the catchment containing the land disposal facility, in cubic meters per second. Combining the above equations, the average concentration in runoff entering the stream and the leachate concentration may be related by:

$$C_{SR} = \zeta_R \cdot C_L \tag{9}$$

where ζ_R is the runoff dilution factor:

$$\zeta_R = Q_R/Q_{SR} \tag{10}$$

Methods for estimating these parameters are developed in later sections. A conservative analysis could assume that the leachate runoff is not mixed with and diluted by runoff from upland areas of the catchment containing the land disposal facility. The runoff mass loading is not affected by this assumption, and stream concentrations below the initial mixing zone should not be very sensitive to this assumption.

Direct loading from a treatment facility--All treatment facilities discharging into a stream must comply with EPA rules and regulations. Waste load allocations are based upon the detrimental effects to humans or aquatic species and must specify the maximum loading rate and concentration of direct discharge into a stream, $\dot{m}_D$ and C_D. In this analysis, maximum loading rates and concentrations in both the industrial waste stream and in the wastewater effluent may be estimated from maximum allowable stream concentrations by the back calculation procedure.

Two types of contaminant discharge are considered. The first is a constant loading over a long period of time. The second type of contaminant discharge is a pulse loading over a short period of time, t_D. The waste-water flow rates, and contaminant concentrations for both types of discharge are assumed to be constant during the time of discharge.

The mass flux in the industrial waste stream, $\dot{m}_W$, and the mass flux in the treated wastewater effluent, $\dot{m}_D$, may be related by:

$$\dot{m}_D = \zeta_W \cdot \dot{m}_W \tag{11}$$

where ζ_W is the treatment plant attenuation factor (1-fractional removal) accounting for the effects of sorption and settling, volatilization, and bacterial degradation. No general equation is developed in this model for calculating ζ_W. If no measured (or independently estimated) value is specified by the user, ζ_W defaults to 1 and mass is conserved through the treatment plant. The concentrations in industrial waste and the wastewater effluent can be obtained by dividing the mass fluxes by the flow rates:

$$C_W = \dot{m}_W / Q_W \tag{12}$$

$$C_D = \dot{m}_D / Q_D \tag{13}$$

Combining the above equations, the concentrations in the wastewater effluent and in the industrial waste may be related by:

$$C_D = \zeta_D \cdot C_W \tag{14}$$

where ζ_D is the wastewater treatment plant reduction factor accounting for both dilution and mass reduction due to treatment efficiency e_W:

$$\zeta_D = \zeta_W \cdot Q_W/Q_D = (1 - e_W) \frac{Q_W}{Q_D} \tag{15}$$

All of these parameters are specified by the user, as discussed in later sections.

2.1.2 Initial Dilution in Stream--

As the contaminated ground water, surface runoff, or treatment facility effluent enters a stream (Figure 5), it mixes with upstream water with pollutants at concentration C_U. Loading of contaminants to the stream resulting from ground water interception, surface runoff, and direct discharge is examined separately in the model. Ground water interception with the stream is assumed to occur continuously along the sides and bottom of the stream. Contaminant loading in surface runoff is assumed to occur intermittently at the stream bank over a short time t_R. Direct discharge is regarded as either continuous or intermittent at the stream bank, occuring over time period t_D.

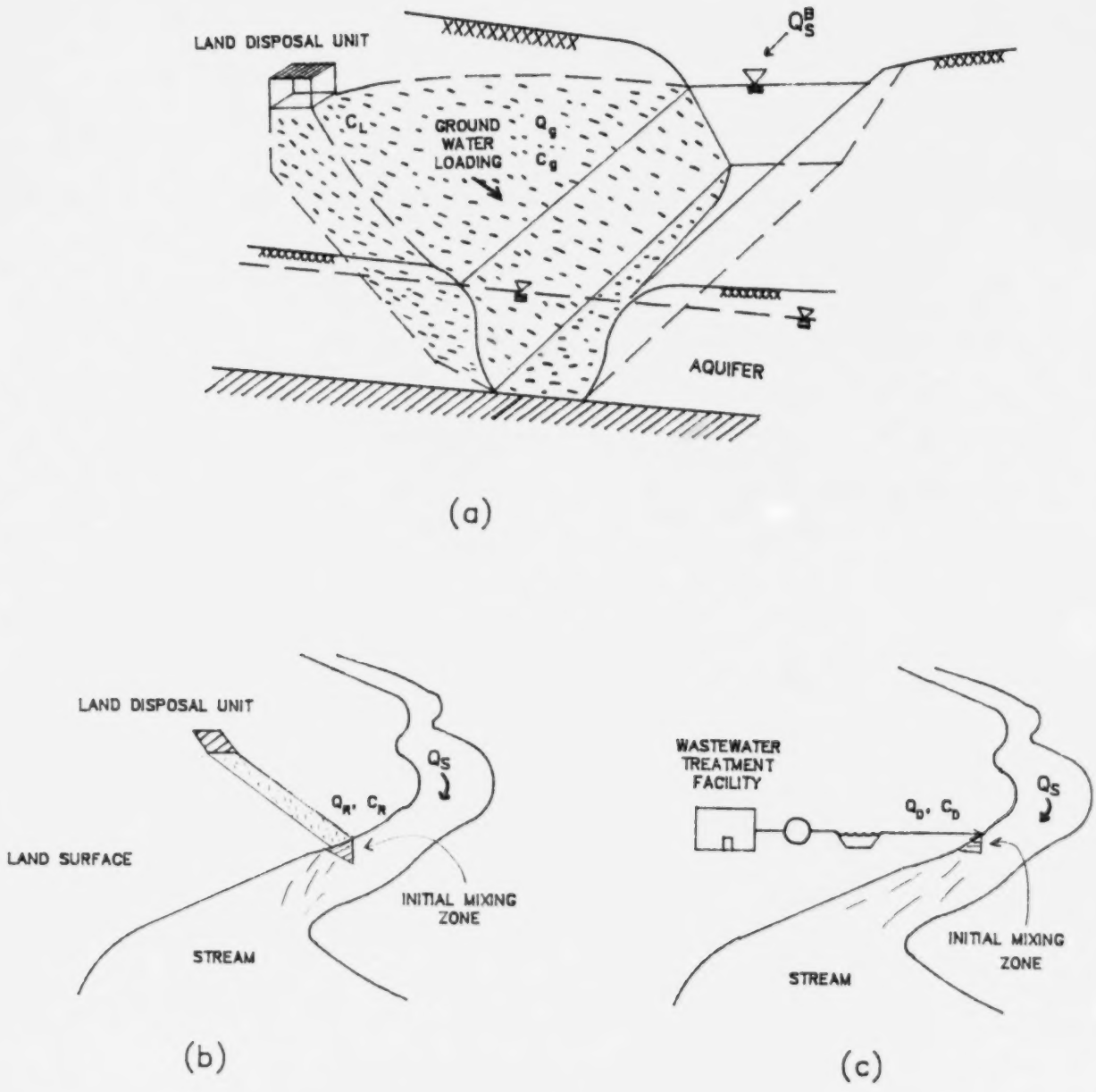


Figure 5. Loading of contaminant into stream--(a) ground water loading, (b) surface runoff loading, (c) direct discharge.

An initial mixing zone in the stream is developed over the contaminant discharge area. For upland watersheds where the the stream is shallow, complete, vertical mixing of the contaminant occurs within this mixing zone. Lateral mixing may be incomplete, however, as indicated in Figure 5b,c. In the cases of runoff loading and direct discharge, where lateral mixing is likely to be incomplete, there is a finite plume width over which a Gaussian concentration distribution $C_{0,y}$ is assumed. The maximum contaminant concentration and the standard deviation of the Gaussian distribution are denoted by C_R (runoff), C_D (discharge), σ_R (runoff), and σ_D (discharge), respectively. The standard deviation, σ, is a measure of the plume width at the edge of the mixing zone.

Ground water mixing--The contaminant mass flux loaded into the stream from ground water, $\dot{m}_{Sg}$, and the mass flux at the ground water interception zone, $\dot{m}_g$, can be related by:

$$\dot{m}_{Sg} = \zeta_i \cdot \dot{m}_g \tag{16}$$

where ζ_i is the fraction of groundwater from the catchment that actually contributes to stream flow. The total mass flux at the downstream edge of the mixing zone is the sum of the upstream mass flux, $\dot{m}_U$, and the mass flux loaded into the stream, $\dot{m}_{Sg}$:

$$\dot{m}_0 = \dot{m}_{Sg} + \dot{m}_U \tag{17}$$

The concentrations can be obtained by dividing the mass fluxes by the stream flow:

$$\overline{C}_0 = \zeta_{Sg} \cdot \overline{C}_g + \zeta_{SU} \cdot C_U \tag{18}$$

where $\overline{C}_0$ is the laterally-averaged concentration at the downstream edge of the mixing zone, and ζ_{Sg} and ζ_{SU} are dilution factors for ground water and upstream concentrations, respectively:

$$\zeta_{Sg} = Q_{Sg}/Q_S \tag{19}$$

$$\zeta_{SU} = Q_U/Q_S \tag{20}$$

where Q_U is the upstream flow rate and Q_{Sg} is the ground water flow from the catchment intercepted by the stream:

$$Q_{Sg} = \zeta_i \cdot Q_g \tag{21}$$

and Q_S is the downstream flow rate, or the sum of Q_{Sg} and Q_U.

Runoff mixing--The contaminant mass flux loaded into the stream from surface runoff, $\dot{m}_{SR}$, is assumed equal to the runoff mass flux at the edge of the stream, $\dot{m}_R$. The total mass flux at the downstream edge of the mixing zone is the sum of the upstream mass flux, assumed equally distributed across the stream, and the runoff mass flux, distributed along the near bank:

$$\dot{m}_0 = \dot{m}_{SR} + \dot{m}_U \tag{22}$$

The concentration distribution across the mixing zone can be obtained by dividing the mass fluxes by the stream flow:

$$C_{0,y} = \zeta_{SR,y} \cdot C_{SR} + \zeta_{SU} \cdot C_U \quad (23)$$

where ζ_{SU} is a dilution factor for upstream concentrations:

$$\zeta_{SU} = Q_U/Q_S \quad (24)$$

and $\zeta_{SR,y}$ is a dilution factor for runoff concentrations describing a lateral, Gaussian distribution across the stream. This dilution factor, developed in later sections, declines from 1 at y = 0 to 0 for large values of y. Q_S is the downstream flow rate, or the sum of Q_{SR} and Q_U.

Direct discharge mixing--The contaminant mass flux loaded into the stream from wastewater effluent, $\dot{m}_{SD}$, is assumed equal to the effluent mass flux, $\dot{m}_D$. The total mass flux at the downstream edge of the mixing zone is the sum of the upstream mass flux, assumed equally distributed across the stream, and the effluent mass flux, distributed along the near bank:

$$\dot{m}_0 = \dot{m}_{SD} + \dot{m}_U \quad (25)$$

The concentration distribution across the mixing zone can be obtained by dividing the mass fluxes by the stream flow:

$$C_{0,y} = \zeta_{SD,y} \cdot C_D + \zeta_{SU} \cdot C_U \quad (26)$$

where ζ_{SU} is a dilution factor for upstream concentrations:

$$\zeta_{SU} = Q_U/Q_S \quad (27)$$

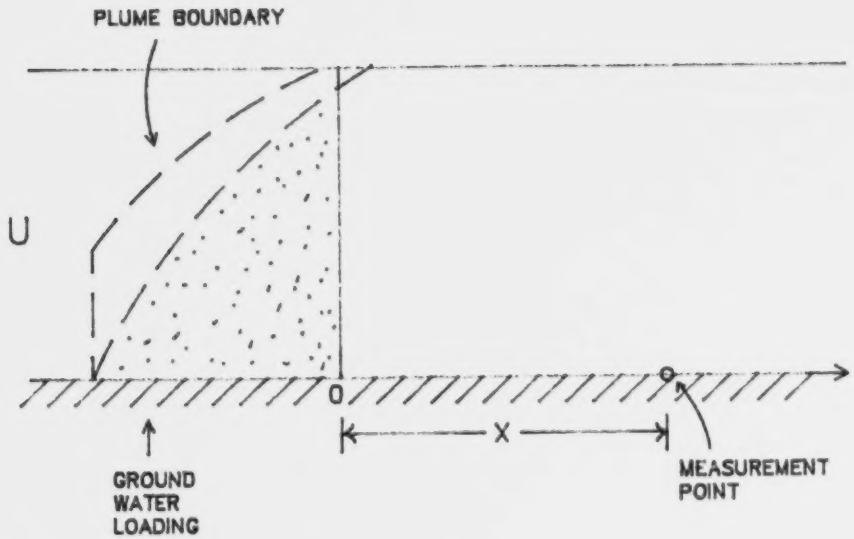
and $\zeta_{SD,y}$ is a dilution factor describing a lateral, Gaussian distribution for effluent concentrations. This dilution factor, developed in later sections, declines from 1 at y = 0 to 0 for large values of y. Q_S is the downstream flow rate, or the sum of Q_D and Q_U.

2.1.3 Transport of Contaminants Downstream--

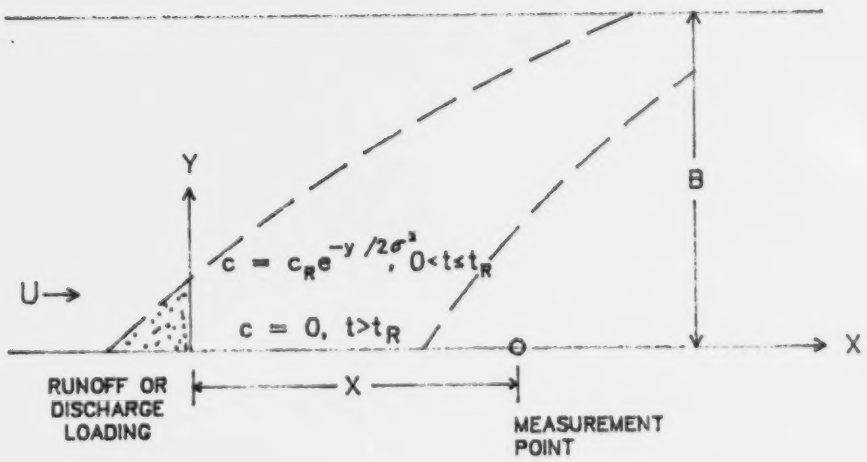
Following initial dilution in the stream, the contaminant is transported downstream from the edge of the initial mixing zone. In the cases of runoff loading and direct discharge, the initial boundary condition assumes a Gaussian distribution $C_{0,y}$. In the case of ground water loading, the initial boundary condition is the laterally averaged $\bar{C}_0$. At a specified downstream measurement point, x, (Figure 6) the contaminant concentration, C_x, is expressed as:

$$\bar{C}_x = \zeta_x \cdot \bar{C}_0 \quad \text{for ground water loading} \quad (28)$$

$$C_{x,y} = \zeta_{x,y} \cdot C_{0,y} \quad \text{for surface runoff and effluent discharge} \quad (29)$$



(a) Continuous Groundwater Loading



(b) Pulse Runoff Loading

Figure 6. Downstream contaminant transport from the edge of initial mixing zone.

where ζ_x and $\zeta_{x,y}$ are concentration reduction factors accounting for the combined influence of advection, longitudinal and lateral dispersion, degradation and sorption occurring during downstream transport. Note that in the case of ground water loading, lateral mixing is probably almost complete at x = 0, because of a fairly extensive contaminant discharge area as compared to the cases of runoff loading.

2.1.4 Exposure and Effects--

Human exposure to contaminants through drinking water--Humans are exposed to dissolved chemicals through the consumption of water obtained from a treatment plant that is located in the zone of contamination downstream from the initial mixing zone. The plant takes in water from the stream, with a contaminant concentration, $C_{x,y}$. The water is assumed to be treated by a primary settling process allowing suspended solids and adsorbed chemicals to settle out. As a result of this treatment, the contaminant concentration is reduced from $C_{x,y}$ to C_{DW}. The relationship of C_{DW} and $C_{x,y}$ is expressed as:

$$C_{DW} = \zeta_{DW} \cdot C_{x,y} \tag{30}$$

where ζ_{DW} is the factor accounting for the reduction in contaminant concentration achieved through the treatment process, i.e., the pollutant removal efficiency.

Human exposure to contaminants through consumption of fish--Another route resulting in human exposure to chemicals in leachate and discharge is the consumption of contaminated fish. To be conservative, it is assumed that these fish reside continuously within the most polluted reach of the stream where concentrations are not reduced by dilution or chemical transformation. The allowable daily intake adopted here is based on an average 70-year consumption of contaminated fish.

For the case of runoff loading, the infrequency of runoff events (2 or 3 occurrences in 70 years) and the length of time required for food fish to attain high body burdens (weeks to months) should prevent significant contaminant doses to humans. For the case of ground water and direct discharge loading, the continuous nature of discharge and ground water seepage into stream may cause fish to attain high body burdens and result in significant contaminant doses to humans over a life time. Delivery of contaminants through consumption of fish, then, is a long-term average, steady-state process. The model allows for the fact that a fish population can be quite mobile over the length and width of a contaminated stream. Furthermore, a single fish may be exposed to a wide range of concentrations during its life time. The typical fish will be exposed to the average concentration denoted by $\bar{C}_0$ in the case of ground water loading (given by equation 18) and by $\bar{C}_{x,y}$ in the case of direct discharge.

Chemicals enter a fish through biochemical exchanges across its gill and gut membranes and through its skin. When these exchange processes have reached equilibrium, the average concentration in the whole body of the fish becomes C_F, which is related to the exposure concentration by:

$$C_F = \zeta_F \cdot \overline{C}_0 \quad (31)$$

$$C_F = \zeta_F \cdot \overline{C}_{x,y} \quad (32)$$

where ζ_F is a bioaccumulation factor depending on both the nature of the chemical and the species of fish.

Conceptually, one more step is required in calculating average chemical dose through fish consumption. Most fish are cleaned, with much of the fat removed before consumption. Because organic chemicals are concentrated in fat, another reduction factor could be used to derive fillet concentrations from whole fish concentrations. To be conservative, however, it is assumed that there is no reduction in chemical concentration due to the preparation of fish for consumption.

Direct exposure of aquatic organisms--If contaminant concentrations are high enough, aquatic organisms may suffer chronic toxic effects. Water quality criteria have been established by EPA to protect against these effects. These criteria specify acceptable concentrations, durations of averaging periods, and frequency of allowed excursions. To prevent a potential hazard to aquatic life, the average contaminant concentration in the surface water is directly equated to the Criterion Continuous Concentration (CCC) Water Quality Criteria. The duration of the averaging period is set at 4 days, and the frequency of allowed excursions is no more than once in 3 years. To be conservative, it is assumed that the fish reside continuously within the most polluted reach of the stream where concentrations are not reduced by degradation.

For the case of runoff loading, the infrequency of runoff events (2 or 3 occurrences in 70 years) and their duration (approximately 1 day) should prevent chronic toxic effects in aquatic organisms. For the case of ground water loading and direct discharge, the continuous nature of seepage into streams may result in chronic toxic effects. Because ground water loading is expected to be relatively steady, highest stream concentrations should occur when the stream reaches low, base flow conditions, providing the least dilution water. For these conditions, both loading and dilution are driven by ground water flow. The dilution factor should be steady for a wide range of base flows, as illustrated by Figure 7. The model allows for the fact that a fish population can be mobile over the width of a contaminated stream during a 4 day period. Thus, the typical fish in the most contaminated stream reach will be exposed to the averaged concentration $\overline{C}_{EXP}$:

$$\overline{C}_{EXP} = \zeta_{EXP} \cdot \overline{C}_0 \quad (33)$$

or

$$\overline{C}_{EXP} = \zeta_{EXP} \cdot \overline{C}_{x,y} \quad (34)$$

where ζ_{EXP} is an aquatic exposure factor, here equal to 1 and for ground water and discharge loading, respectively.

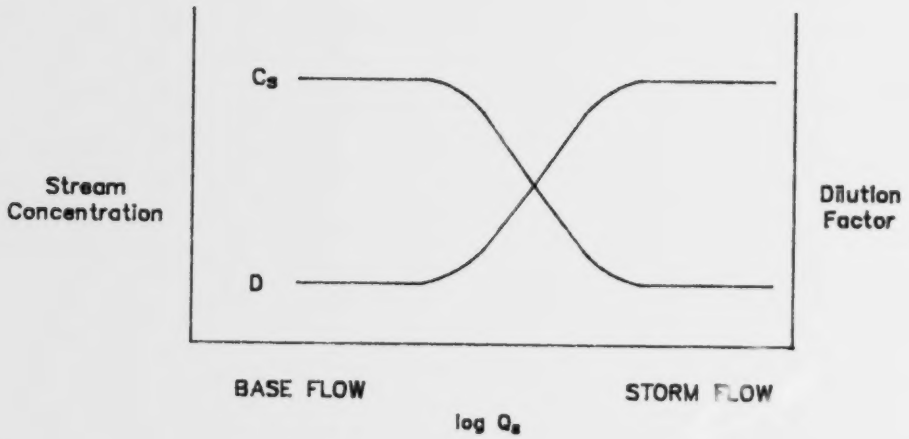


Figure 7. Variation of dilution factor with stream flow for steady ground water loading.

2.2 EXPOSURE SCENARIOS

Five sets of scenarios are considered. The five sets (1, 2, 3, 4, and 5) are distinguished from one another by the pathway through which contaminants reach and eventually enter into the stream. Each set consists of three potential exposure routes (A, B, and C) that threaten humans or aquatic organisms. These are summarized in Table 1.

2.2.1 Scenario 1A: Exposure to Humans through Drinking Water Contaminated by Leachate Carried through Ground Water to the Stream--

This scenario consists of four stages between failure of the waste containment facility and the exposure of the contaminant to humans via drinking water (Figure 8). Through these stages, the concentration is successively reduced from the leachate concentration, C_L, to the concentration in drinking water, C_{DW}. The relationship between C_{DW}, C_U, and C_L is given by:

$$C_{DW} = \zeta_g \zeta_{Sg} \zeta_x \zeta_{DW} C_L + \zeta_{SU} \zeta_x \zeta_{DW} C_U \qquad (35)$$

where ζ_g, ζ_{Sg}, ζ_{SU} ζ_x, and ζ_{DW} are reduction factors due to transport in ground water, mixing at the area of leachate entry into the stream, transport in the stream, and treatment in the drinking water plant.

To determine whether a potential health hazard due to surface water contamination exists, the drinking water concentration can be equated to the specified acceptable daily intake concentration, C_{ADI}. Thus:

TABLE 1. SUMMARY OF POTENTIAL EXPOSURE SCENARIOS

SCENARIO	SOURCE PATHWAY	EXPOSURE ROUTE
1A	ground water seepage	human exposure via drinking water
1B		human exposure via fish consumption
1C		direct exposure of aquatic organisms
2A	steady surface runoff from a design storm event	human exposure via drinking water
2B		human exposure via fish consumption
2C		direct exposure of aquatic organisms
3A	pulse surface runoff from a design storm event	human exposure via drinking water
3B		human exposure via fish consumption
3C		direct exposure of aquatic organisms
4A	steady discharge from a wastewater treatment facility	human exposure via drinking water
4B		human exposure via fish consumption
4C		direct exposure of aquatic organisms
5A	batch discharge from a wastewater treatment facility	human exposure via drinking water
5B		human exposure via fish consumption
5C		direct exposure of aquatic organisms

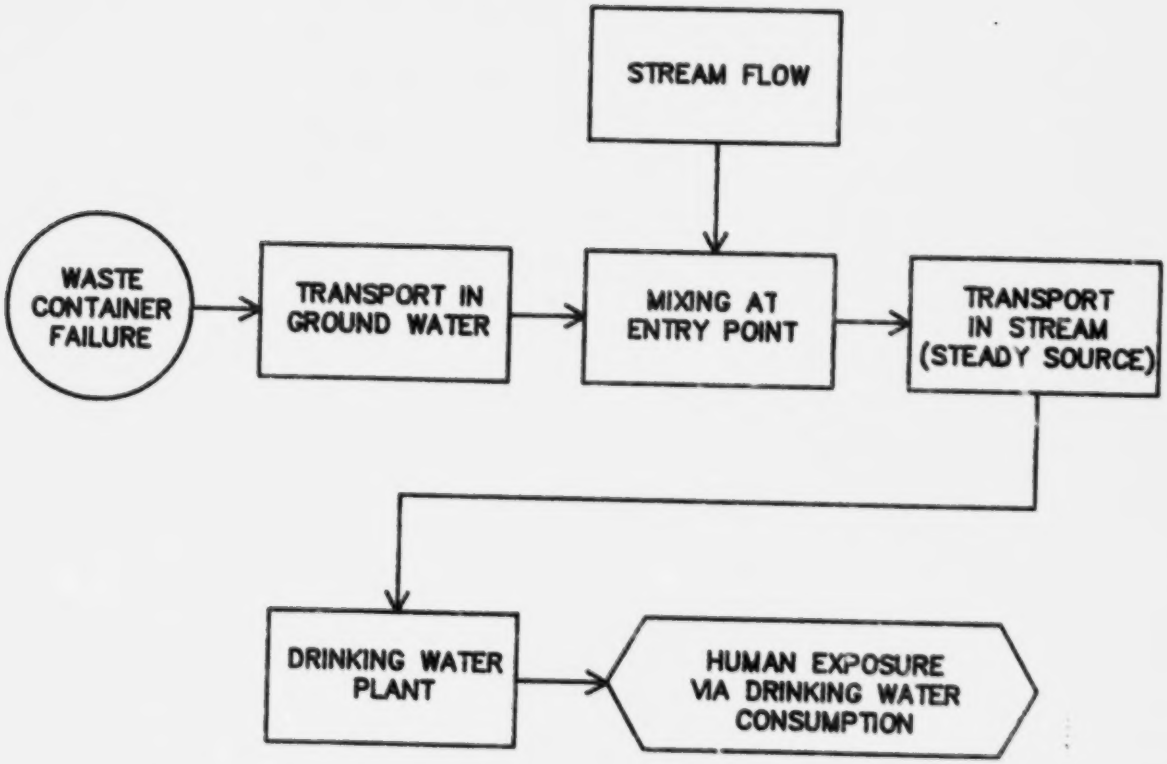


Figure 8. Flow chart for scenario 1A.

$$C_{DW} = C_{ADI} \tag{36}$$

and the maximum allowable leachate concentration must be:

$$C_L = \frac{C_{ADI} - \zeta_{SU}\,\zeta_x\,\zeta_{DW}\,C_U}{\zeta_g\,\zeta_{Sg}\,\zeta_x\,\zeta_{DW}} \tag{37}$$

2.2.2 Scenario 1B: Exposure to Humans through Consumption of Fish Contaminated by Leachate Carried through Ground Water to the Stream

This scenario consists of three stages between the containment failure and human exposure via consumption of fish residing in the contaminated surface water (Figure 9). Through these stages, the input concentration is successively reduced from the leachate concentration, C_L, to the stream concentration, and then increased to the bioconcentrated level in the fish, C_F. The relation between C_L, C_U, and C_F is given by:

$$C_F = \zeta_g\,\zeta_{Sg}\,\zeta_F\,C_L + \zeta_{SU}\,\zeta_F\,C_U \tag{38}$$

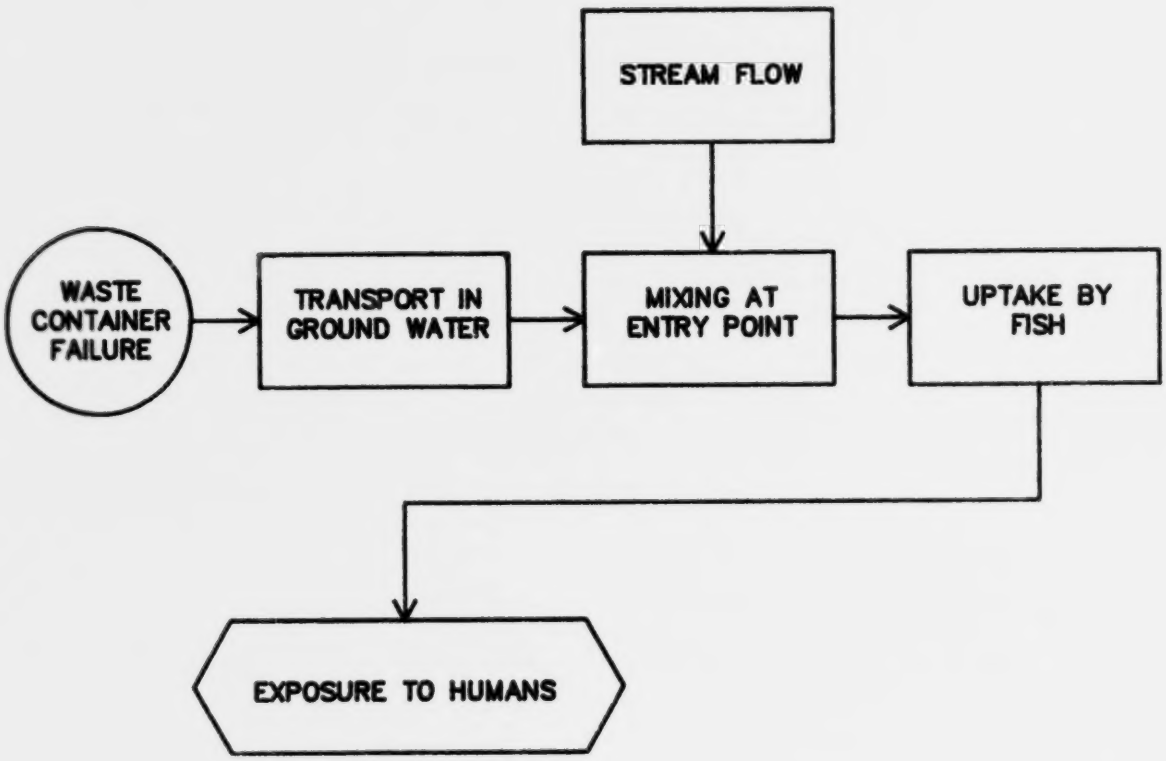


Figure 9. Flow chart for scenario 1B.

where ζ_F is the bioconcentration factor due to the biochemical exchange processes with the fish.

For back-calculation, the average concentration in the fish, C_F, can be equated to a specified acceptable daily intake bioaccumulation concentration, C'_{ADI}. Thus:

$$C_F = C'_{ADI} \tag{39}$$

and the maximum allowable leachate concentration is given by:

$$C_L = \frac{C'_{ADI} - \zeta_{SU}\,\zeta_F\,C_U}{\zeta_g\,\zeta_{Sg}\,\zeta_F} \tag{40}$$

2.2.3 Scenario 1C: Exposure of Aquatic Life due to Leachate Carried through Ground Water to the Stream--

This scenario consists of two stages between the waste containment unit failure and aquatic exposure (Figure 10). Through these stages, the input

concentration is successively reduced from the leachate concentration, C_L, to the average stream concentration, $\overline{C}_0$. The relationship between C_L, C_U, and $\overline{C}_0$ is given by:

$$\overline{C}_0 = \zeta_g \, \zeta_{Sg} \, C_L + \zeta_{SU} \, C_U \tag{41}$$

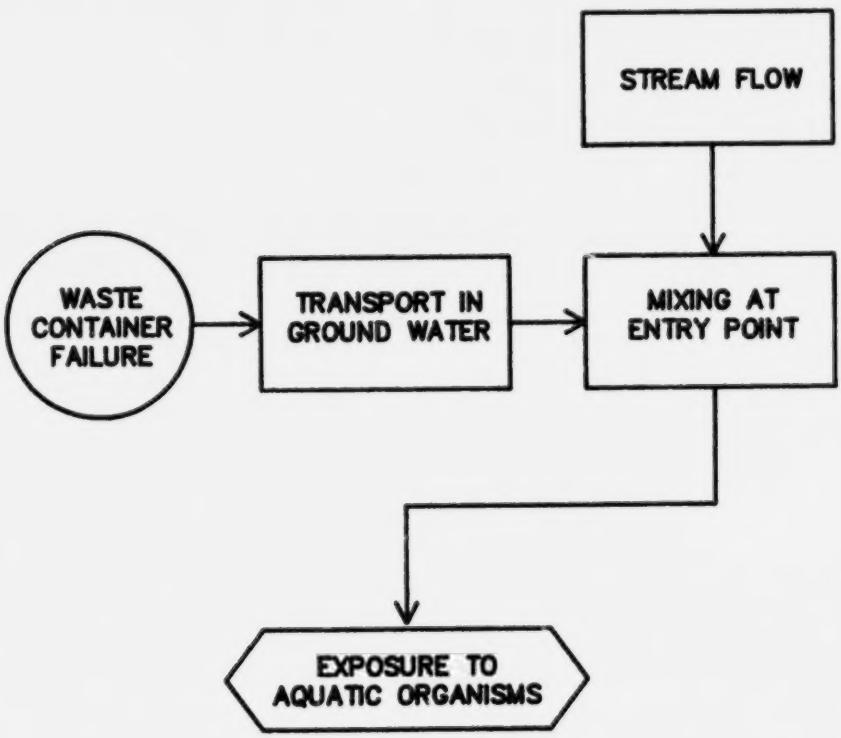


Figure 10. Flow chart for scenario 1C.

For back-calculation, the average concentration in the stream can be equated to a specified Criterion Continuous Concentration Water Quality Criteria, CCC. Thus:

$$\overline{C}_0 = CCC \tag{42}$$

and the maximum allowable leachate concentration is given by:

$$C_L = \frac{CCC - \zeta_{SU} \, C_U}{\zeta_g \, \zeta_{Sg}} \tag{43}$$

2.2.4 Scenario 2A: Exposure to Humans through Drinking Water Contaminated by Leachate Carried through Runoff from the 25-Year, 24-Hour Storm Event--

This scenario consists of four stages between the waste containment failure and exposure of the contaminant to humans via drinking water (Figure 11). Through these stages, the concentration is successively reduced from the leachate concentration, C_L, to the concentration in the drinking water, C_{DW}. The relationship between C_{DW}, C_U, and C_L is given by:

$$C_{DW} = \zeta_R \zeta_{SR,y} \zeta_{x,y} \zeta_{DW} C_L + \zeta_{SU} \zeta_x \zeta_{DW} C_U \quad (44)$$

where ζ_R, ζ_S, ζ_x, and ζ_{DW} are reduction factors due to dilution during runoff, initial mixing at the stream entry area, transport in the stream, and drinking water treatment, respectively.

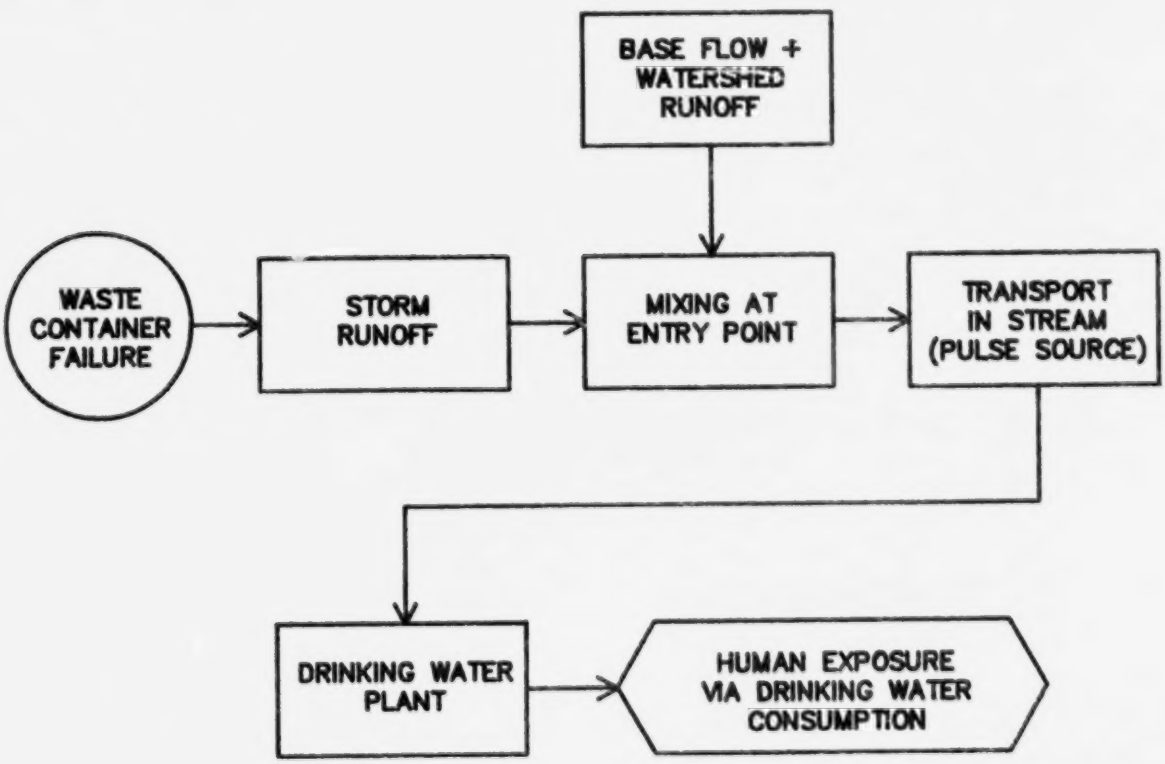

BASE FLOW + WATERSHED RUNOFF
WASTE CONTAINER FAILURE
STORM RUNOFF
MIXING AT ENTRY POINT
TRANSPORT IN STREAM (PULSE SOURCE)
DRINKING WATER PLANT
HUMAN EXPOSURE VIA DRINKING WATER CONSUMPTION

Figure 11. Flow chart for scenario 2A.

Because of the pulse runoff loading condition, the concentration C_{DW} is time dependent. Thus, it is averaged over a 1-day period. This average concentration, $\langle C_{DW} \rangle$, can then be equated to the specified acceptable daily intake concentration, C_{ADI}. It follows that:

$$\langle C_{DW} \rangle = C_{ADI} \tag{45}$$

and the maximum allowable leachate concentration is given by:

$$C_L = \frac{C_{ADI} - \langle \zeta_{SU}\, \zeta_{x,y}\, \zeta_{DW} \rangle C_U}{\langle \zeta_R \zeta_{SR,y}\, \zeta_{x,y}\, \zeta_{DW} \rangle} \tag{46}$$

where angular brackets are used to denote the 1-day average of the enclosed quantity.

2.2.5 Scenario 2B: Exposure to Humans through Consumption of Fish Contaminated by Leachate Carried through Runoff from the 25-Year, 24-Hour Storm Event--

This scenario consists of four stages between the waste containment failure and exposure of contaminant to humans via consumption of fish (Figure 12). Through these stages, the input concentration is altered from the leachate concentration, C_L, to the average concentration in the fish, C_F. The infrequency of runoff events (2 or 3 occurrences in 70 years) and the length of time required for food fish to attain high body burdens (weeks to months) should prevent significant contaminant doses to humans from this scenario. Consequently, back-calculation formulas are not developed.

2.2.6 Scenario 2C: Exposure of Aquatic Life to Leachate Carried by Runoff from a 25-Year, 24-Hour Storm Event--

This scenario consists of three stages between the waste containment unit failure and aquatic exposure (Figure 13). Through these stages, the input concentration is reduced from the leachate concentration, C_L, to the stream concentration $C_{x,y}$. The infrequency of runoff events (2 or 3 occurrences in 70 years) and their duration (approximately 1 day) should prevent chronic toxic effects in aquatic organisms. Consequently, back-calculation formulas are not developed.

2.2.7 Scenario 3A: Exposure to Humans through Drinking Water Contaminated by Leachate Carried through Catastrophic Runoff Loading to the Stream--

This scenario consists of four stages between the waste containment failure and exposure of the contaminant to humans via drinking water (Figure 14). Through these stages, the concentration is successively reduced from C_L to C_{DW}.

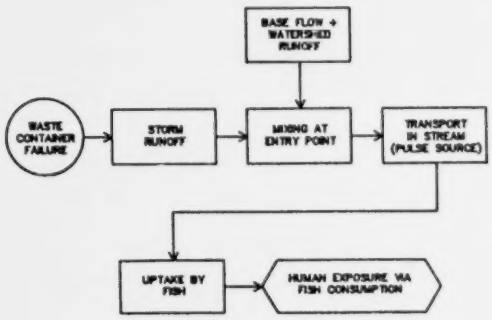


Figure 12. Flow chart for scenario 2B.

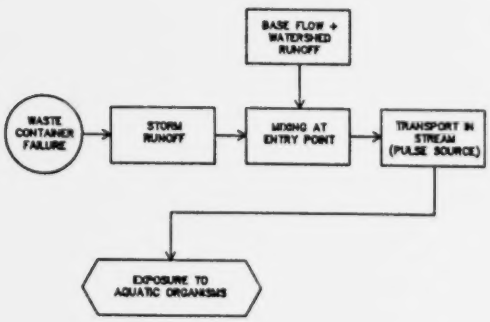


Figure 13. Flow chart for scenario 2C.

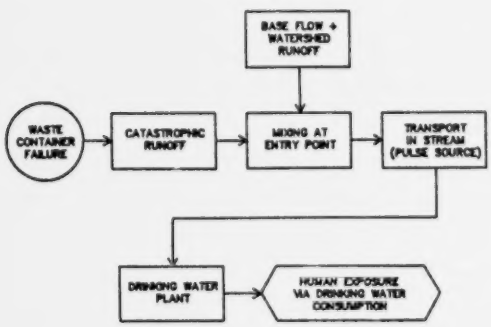

BASE FLOW + WATERSHED RUNOFF
WASTE CONTAINER FAILURE
CATASTROPHIC RUNOFF
MIXING AT ENTRY POINT
TRANSPORT IN STREAM (PULSE SOURCE)
DRINKING WATER PLANT
HUMAN EXPOSURE VIA DRINKING WATER CONSUMPTION

Figure 14. Flow chart for scenario 3A.

In a similar manner to Scenario 2A, a daily averaged concentration in drinking water, $\langle C_{DW} \rangle$, is obtained and equated to C_{ADI} to yield the following equation for the maximum leachate concentration, C_L.

$$C_L = \frac{C_{ADI} - \langle \zeta_{SU}\, \zeta_x\, \zeta_{DW} \rangle\, C_U}{\langle \zeta_R\, \zeta_{SR,y}\, \zeta_x\, \zeta_{DW} \rangle} \qquad (47)$$

where ζ_R, ζ_S, ζ_x, and ζ_{DW} are reduction factors due to, respectively, dilution during runoff, initial mixing at the stream entry area, transport in the stream, and drinking water treatment.

2.2.8 Scenario 3B: Exposure to Humans through Consumption of Fish Contaminated by Leachate Carried through Catastrophic Runoff Loading to the Stream--

This scenario consists of four stages between the waste containment failure and exposure of the contaminant to humans via consumption of fish (Figure 15). Through these stages, the concentration is successively reduced from C_L to C_F. For reasons given in Scenario 2B, significant contaminant doses to humans from this scenario are ruled out. Back-calculation formulas are not developed.

2.2.9 Scenario 3C: Exposure of Aquatic Life due to Leachate Carried through Catastrophic Runoff Loading to the Stream--

This scenario consists of three stages between the waste containment unit failure and aquatic exposure (Figure 16). Through these stages, the input concentration is reduced from the leachate concentration, C_L, to the stream concentration $C_{x,y}$. The infrequency of runoff events (2 or 3 occurrences in 70 years) and their duration (approximately 1 day) should prevent chronic toxic effects in aquatic organisms. Consequently, back-calculation formulas are not developed.

2.2.10 Scenario 4A: Exposure to Humans through Drinking Water Contaminated by a Continuous Discharge--

This scenario consists of four stages between the industrial waste stream and exposure of the contaminant to humans via drinking water (Figure 17). Through these stages, the concentration is successively reduced from the industrial waste concentration, C_W, to the concentration in the drinking water C_{DW}. The relationship between C_{DW}, C_U, and C_W is given by:

$$C_{DW} = \zeta_D\, \zeta_{SD}\, \zeta_{x,y}\, \zeta_{DW}\, C_W + \zeta_{SU}\, \zeta_x\, \zeta_{DW}\, C_U \qquad (48)$$

where ζ_D, ζ_{SD}, ζ_{SU}, $\zeta_{x,y}$, and ζ_{DW} are reduction factors due to wastewater treatment, initial mixing at the stream entry area, transport in the stream, and drinking water treatment, respectively.

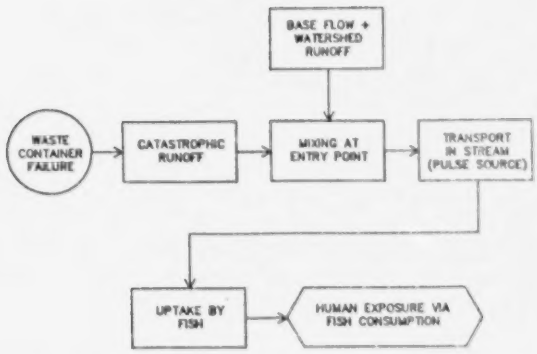


Figure 15. Flow chart for scenario 3B.

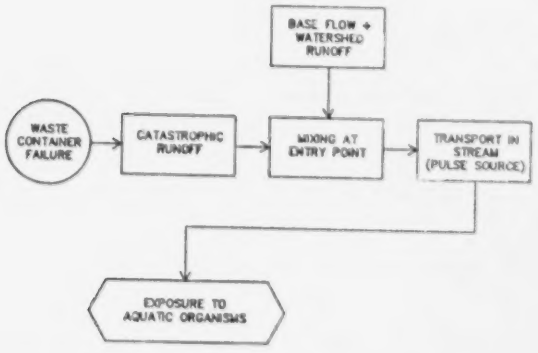


Figure 16. Flow chart for scenario 3C.

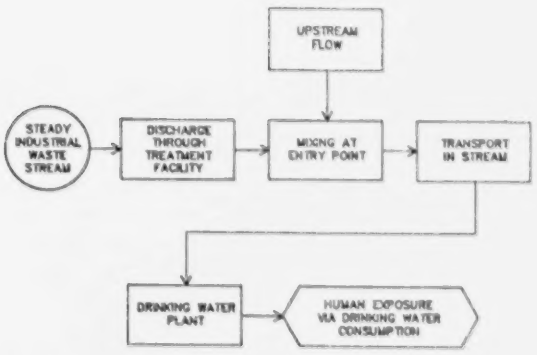


Figure 17. Flow chart for scenario 4A.

To determine whether a potential health hazard due to surface water contamination exists, the drinking water concentration can be equated to the specified acceptable daily intake concentration, C_{ADI}. Thus:

$$C_{DW} = C_{ADI} \tag{49}$$

and the maximum allowable concentration must be:

$$C_W = \frac{C_{ADI} - \zeta_{SU}\,\zeta_x\,\zeta_{DW}\,C_U}{\zeta_D\,\zeta_{SD}\,\zeta_{x,y}\,\zeta_{DW}} \tag{50}$$

2.2.11 Scenario 4B: Exposure to Humans through Consumption of Fish Contaminated by a Continuous Direct Discharge--

This scenario consists of four stages between the industrial waste stream and human exposure via consumption of fish residing in the contaminated surface water (Figure 18). Through these stages, the input concentration is successively reduced from the industrial waste concentration, C_W, to the average stream concentration through a specified reach, and then increased to the bioconcentrated level in the fish, C_F. The relation between C_W, C_U, and C_F is given by:

$$C_F = \zeta_D\,\zeta_{SD}\,\zeta_{x,y}\,\zeta_F\,C_W + \zeta_{SU}\,\zeta_x\,\zeta_F\,C_U \tag{51}$$

For back-calculation, the average concentration in the fish, C_F, can be equated to a specified acceptable daily intake bioaccumulation concentration, C'_{ADI}. Thus:

$$C_F = C'_{ADI} \tag{52}$$

and the maximum allowable discharge concentration is given by:

$$C_W = \frac{C'_{ADI} - \zeta_{SU}\,\zeta_x\,\zeta_F\,C_U}{\zeta_D\,\zeta_{SD}\,\zeta_{x,y}\,\zeta_F} \tag{53}$$

2.2.12 Scenario 4C: Exposure of Aquatic Life due to a Continuous Discharge--

This scenario consists of three stages between the industrial waste stream and aquatic exposure (Figure 19). Through these stages, the input concentration is successively reduced from the industrial waste concentration, C_W, to the average stream concentration, $\overline{C}_{x,y}$. The relation between C_W, C_U, and $\overline{C}_{x,y}$ is given by:

$$\overline{C}_{x,y} = \zeta_D\,\zeta_{SD}\,\zeta_{x,y}\,C_W + \zeta_{SU}\,\zeta_x\,C_U \tag{54}$$

For back-calculation, the average concentration in the stream can be equated to the CCC by:

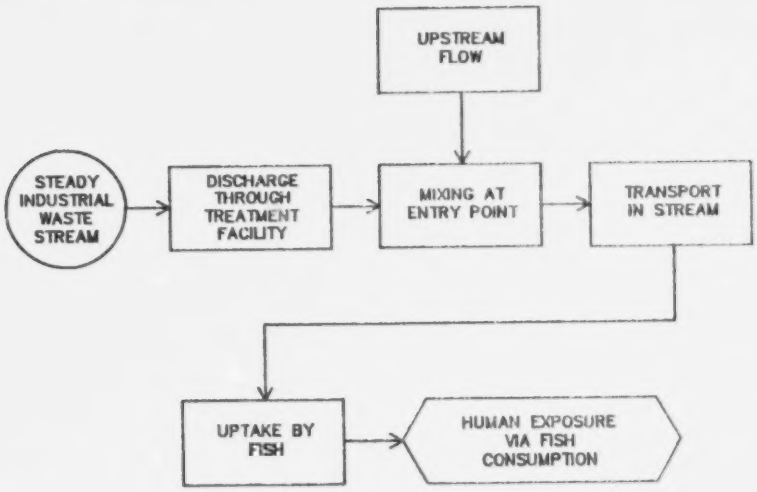


Figure 18. Flow chart for scenario 4B.

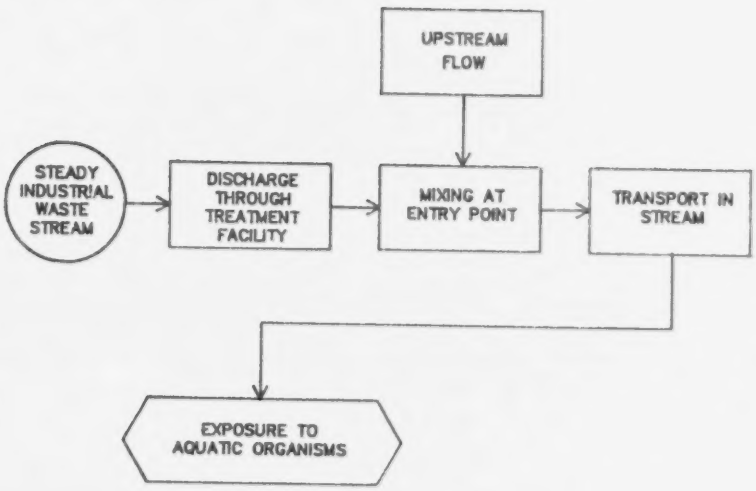


Figure 19. Flow chart for scenario 4C.

$$\overline{C}_{x,y} = CCC \tag{55}$$

and the maximum allowable discharge concentration is given by:

$$C_W = \frac{CCC - \zeta_{SU}\,\zeta_x\,C_U}{\zeta_D\,\zeta_{SD}\,\zeta_{x,y}} \tag{56}$$

2.2.13 Scenario 5A: Exposure to Humans through Drinking Water Contaminated by a Pulse Discharge--

This scenario consists of four stages between the industrial waste stream and exposure of the contaminant to humans via drinking water (Figure 20).

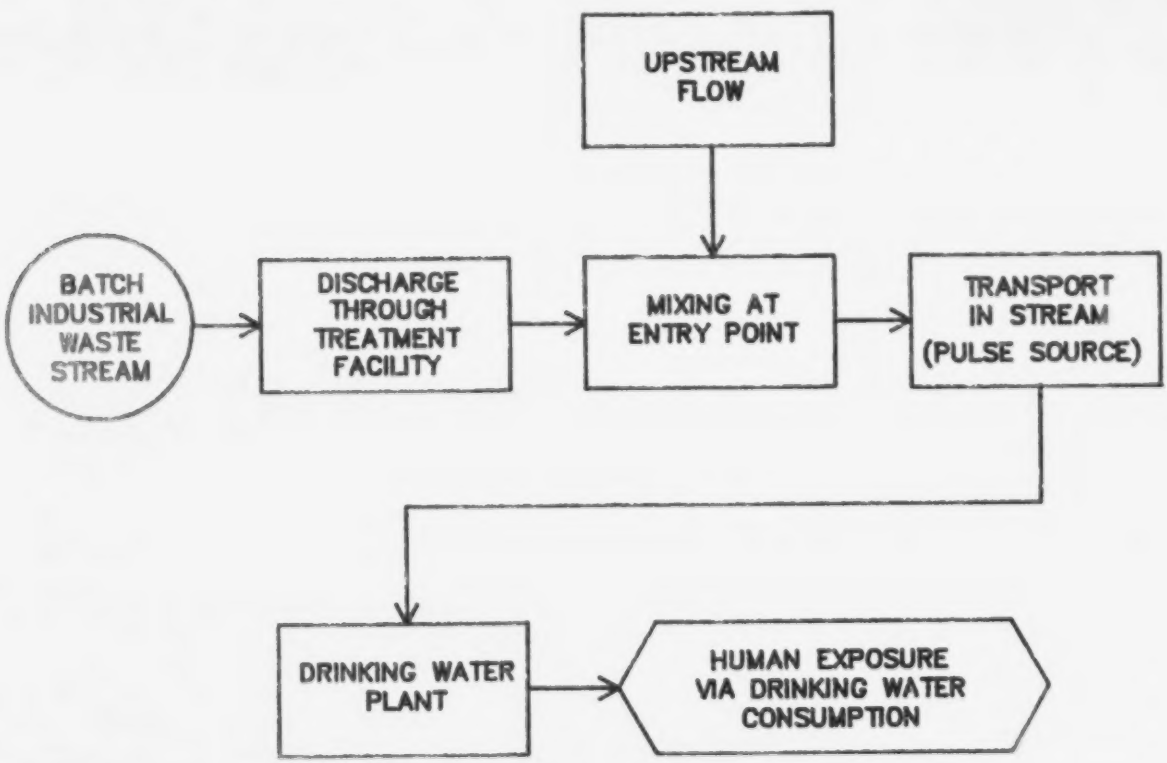

UPSTREAM FLOW
BATCH INDUSTRIAL WASTE STREAM
DISCHARGE THROUGH TREATMENT FACILITY
MIXING AT ENTRY POINT
TRANSPORT IN STREAM (PULSE SOURCE)
DRINKING WATER PLANT
HUMAN EXPOSURE VIA DRINKING WATER CONSUMPTION

Figure 20. Flow chart for scenario 5A.

Through these stages, the concentration is successively reduced from C_W to C_{DW}. In a similar manner to Scenario 4A, a time-averaged concentration in drinking water, $\langle C_{DW} \rangle$, is obtained and equated to C_{ADI} to yield the following equation for the maximum discharge concentration, C_W:

$$C_W = \frac{C_{ADI} - \langle \zeta_{SU}\ \zeta_x\ \zeta_{DW} \rangle\ C_U}{\langle \zeta_D\ \zeta_{SD}\ \zeta_{x,y}\ \zeta_{DW} \rangle} \tag{57}$$

where ζ_D, ζ_{SD}, $\zeta_{x,y}$, and ζ_{DW} are reduction factors due to initial mixing at the stream entry area, transport in the stream, and drinking water treatment, respectively.

2.2.14 Scenario 5B: Exposure to Humans through Consumption of Fish Contaminated by a Pulse Discharge--

This scenario consists of four stages between the industrial waste stream human exposure via consumption of fish residing in the contaminated surface water (Figure 21). Through these stages, the input concentration is successively reduced from the industrial waste concentration, C_W, to the average stream concentration throughout a specified reach, and then increased to the bioconcentrated level in the fish, C_F. A time-averaged bioconcentrated level in the fish, $\langle C_F \rangle$, is obtained and equated to a specified acceptable daily intake bioaccumulation concentration, C_{ADI}. Thus:

$$\langle C_W \rangle = \frac{C'_{ADI} - \zeta_{SU}\ \zeta_x\ \zeta_F\ C_U}{\langle \zeta_D\ \zeta_{SD}\ \zeta_{x,y}\ \zeta_F \rangle} \tag{58}$$

2.2.15 Scenario 5C: Exposure of Aquatic Life due to a Pulse Discharge--

This scenario consists of three stages between the industrial waste stream and aquatic exposure (Figure 22). Through these stages, the input concentration is successively reduced from the industrial waste concentration, C_W, to the time and stream averaged concentration, $\langle \bar{C}_{SD} \rangle$. The relationship between C_W, C_U, and $\langle \bar{C}_{SD} \rangle$ is given by:

$$\langle \bar{C}_{SD} \rangle = \langle \zeta_D\ \zeta_{SD}\ \zeta_{x,y} \rangle + \zeta_{SU}\ \zeta_x\ C_U \tag{59}$$

For back-calculation, the average concentration in the stream can be equated to a specified CCC. Thus:

$$\langle \bar{C}_{SD} \rangle = CCC \tag{60}$$

and the maximum allowable discharge concentration is given by:

$$C_W = \frac{CCC - \zeta_{SU}\ \zeta_x\ C_U}{\langle \zeta_D\ \zeta_{SD}\ \zeta_{x,y} \rangle} \tag{61}$$

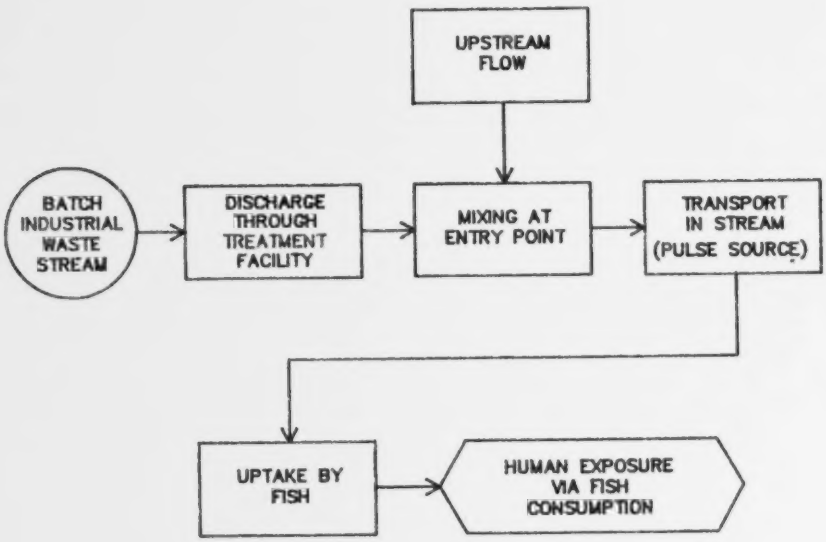


Figure 21. Flow chart for scenario 5B.

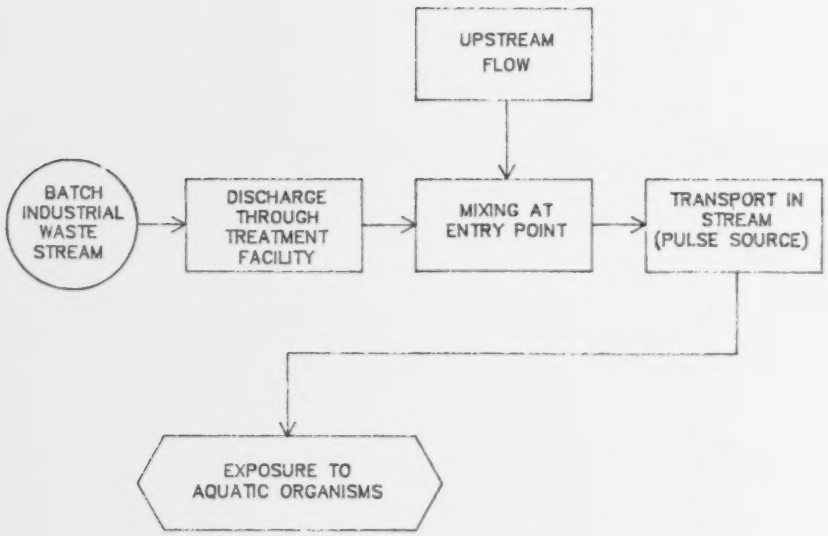


Figure 22. Flow chart for scenario 5C.

2.2.16 Overview of the Analyses--

Scenario 1A: Exposure to humans through drinking water due to ground water interception with the stream

- Release from waste facility containment to ground water
- Transport in ground water to surface water body
- Mixing with the stream
- Transport in stream to drinking water intake
- Treatment of drinking water

Scenario 1B: Exposure to humans through fish consumption due to ground water interception with the stream

- Release from waste facility containment to ground water
- Transport in ground water to surface water body
- Mixing with the stream
- Uptake by fish through gills, gut, and skin

Scenario 1C: Exposure to aquatic organisms due to ground water interception with the stream

- Release from waste facility containment to ground water
- Transport in ground water to surface water body
- Mixing with the stream

Scenario 2A: Exposure to humans through drinking water due to steady runoff from a design storm event

- Surface runoff from waste containment facility
- Overland transport assuming no reduction in mass
- Mixing with the stream
- Transport in stream to drinking water intake
- Treatment of drinking water

Scenario 2B: Exposure to humans through fish consumption due to steady runoff from a design storm event

Not modeled.

Scenario 2C: Exposure to aquatic organisms due to steady runoff from a design storm event

Not modeled.

Scenario 3A: Exposure to humans through drinking water due to pulse runoff from a design storm event

- Surface runoff loading from waste containment facility
- Overland transport assuming no reduction in mass
- Mixing with the stream
- Transport in the stream to drinking water intake
- Treatment of drinking water

Scenario 3B: Exposure to humans through fish consumption due to pulse runoff from a design storm event

Not modeled.

Scenario 3C: Exposure to aquatic organisms due to pulse runoff from a design storm event

Not modeled.

Scenario 4A: Exposure to humans through drinking water due to a steady waste discharge

- Discharge to treatment facility
- Dilution and degradation in treatment facility
- Mixing with the stream
- Transport in stream to drinking water intake
- Treatment of drinking water

Scenario 4B: Exposure to humans through fish consumption due to a steady waste discharge

- Discharge to treatment facility
- Dilution and degradation in treatment facility
- Mixing with stream
- Uptake by fish through gills, gut, and skin

Scenario 4C: Exposure to aquatic organisms due to a steady state discharge

- Discharge to treatment facility
- Dilution and degradation in treatment facility
- Mixing with the stream

Scenario 5A: Exposure to humans through drinking water due to a batch waste discharge

- Discharge to treatment facility
- Dilution and degradation in treatment facility
- Mixing with the stream
- Transport in stream to drinking water intake
- Treatment of drinking water

Scenario 5B: Exposure to humans through fish consumption due to a batch waste discharge

- Discharge to treatment facility
- Dilution and degradation in treatment facility
- Mixing with stream
- Uptake by fish through gills, gut, and skin

Scenario 5C: Exposure to aquatic organisms due to a batch waste discharge

- Discharge to treatment facility
- Dilution and degradation in treatment facility
- Mixing with the stream

2.3 DEVELOPMENT OF EQUATIONS

In this section, equations for determining the reduction factors corresponding to various contaminant pathways are presented. Where appropriate, the key equations are derived. Major symbols used are listed in Appendix C. The scenarios for leachate loading and initial dilution are considered first. Next, equations for stream transport and transformation are developed. Finally, contaminant delivery to drinking water and fish is considered.

2.3.1 Leachate Loading and Dilution upon Entry into the Stream--

Loading of contaminants into the stream can be supplied from ground water flow through an aquifer intercepting the stream, from surface runoff and overland flow, or from direct discharge from a wastewater treatment facility. For the ground water and continuous discharge loading, the steady-state loading assumption will be used. The surface runoff and batch discharge loading assumes intermittent pulse loading.

Ground water loading and initial dilution--Contaminants reaching a stream via ground water will essentially enter the water body continuously, if hydraulic impacts of such interception are ignored. This assumes that the ground water flow field is not influenced by the adjacent surface water. Therefore, for the ground water pathway, the average edge-of-stream concentration can be calculated from the leachate concentration via a ground water equation that considers advection, retardation, and chemical hydrolysis.

For this analysis, it is not necessary to calculate a full three-dimensional concentration distribution for the ground water. In fact, only the average ground water concentration across the plume is needed to the point of its interception with the stream. The average ground water attenuation factor, which is used in equation 1, can be calculated using a one-dimensional mass balance. This mass balance is equivalent to using a three-dimensional ground water equation, then averaging over the width and depth of the plume.

As the contaminated water from the aquifer system enters the stream along the side and bottom, it mixes with fresh surface water supplied by the upland watershed as illustrated in Figure 23. Lateral mixing spreads the contaminants until lateral concentration gradients disappear. The laterally-averaged concentration, $\overline{C}_x$, increases with increasing distance reaching a maximum near the downstream edge of the contaminated ground water plume, where $x = 0$. At the section where $x = 0$, $\overline{C}_x$ corresponds to $\overline{C}_0$ and can be calculated by a simple mass balance.

The equations developed in Sections 2.1.1 and 2.1.2 relate contaminant concentrations in the leachate with concentrations in groundwater, and these with concentrations in stream. Combining equations 4, 5, 18-21 gives:

$$\overline{C}_0 = \zeta_H \cdot \zeta_i \cdot \frac{Q_L}{Q_S} \cdot C_L + \frac{Q_U}{Q_S} \cdot C_U \qquad (62)$$

where C_L and Q_L are the leachate concentration and flow rate, ζ_H is a ground water attenuation factor accounting for the effects of hydrolysis in the aquifer, ζ_i is the fraction of the ground water flow from the contaminated catchment that is intercepted by the stream, Q_g is the total ground water flow from the contaminated catchment, C_U and Q_U are the upstream concentration and flow, and Q_S is the total stream flow below the contaminated catchment. These terms are discussed below.

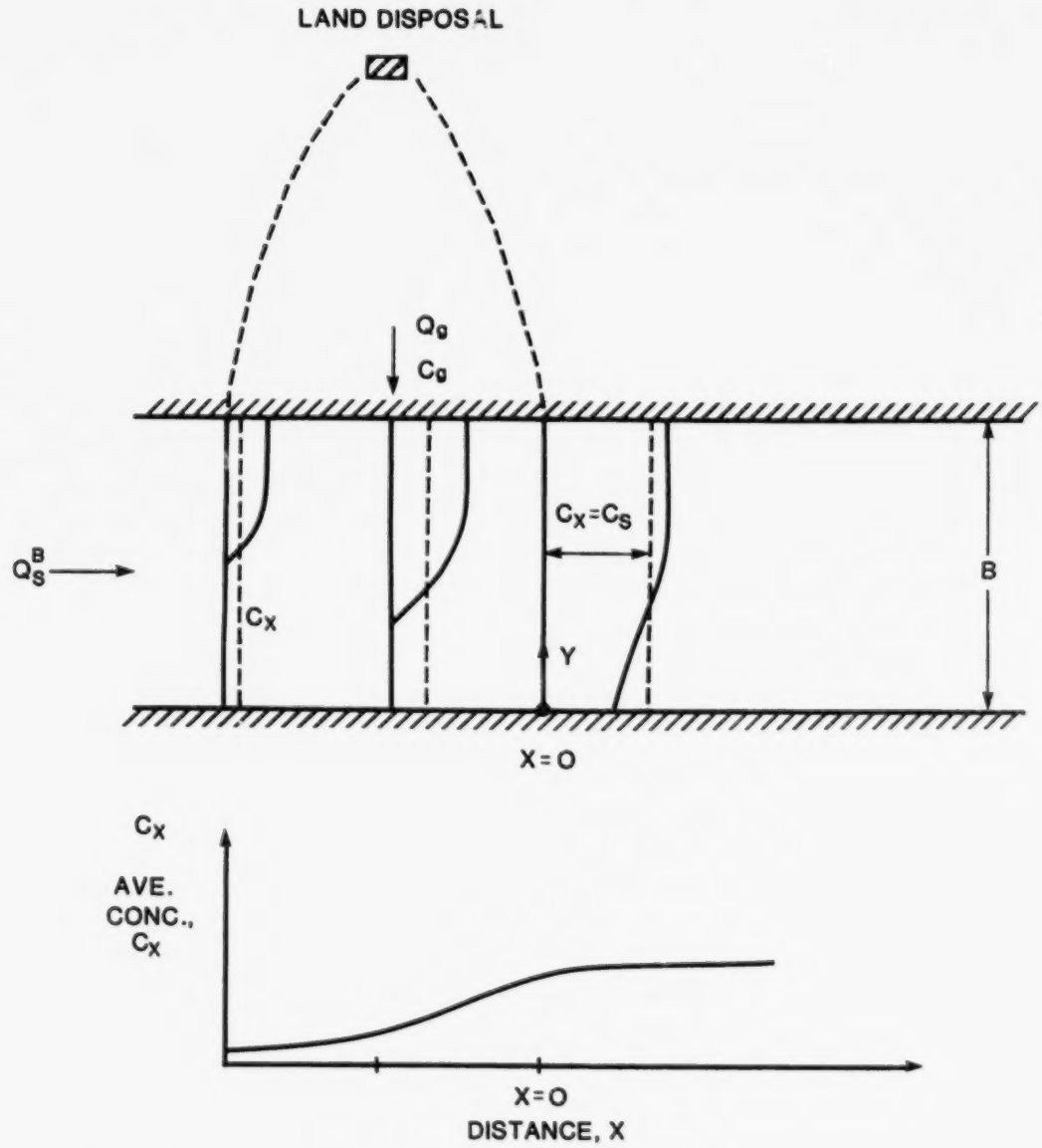


Figure 23. Ground water loading to the stream showing mass balance and concentration profiles.

ζ_H--This attenuation factor is the fraction of the contaminant mass not transformed by hydrolysis during ground water transport to the stream. Assuming a homogeneous aquifer, this factor can be calculated by:

$$\zeta_H = \exp\ (-K_g \cdot \tau_g) \tag{63}$$

where K_g is the total effective decay constant in ground water, in $years^{-1}$, and τ_g is the time taken by the contaminant to travel from the land disposal site to the stream entry point, in years. For those chemicals that hydrolyze, K_g is equal to the overall hydrolysis rate constant given by equations A23 and A25 in Appendix A. The travel time of contaminants in ground water is given by:

$$\tau_g = \frac{X_g}{V_g \cdot f_{Dg}} \tag{64}$$

where X_g is the distance from the site to the stream, in meters, V_g is the ground water seepage velocity, in meters per year, and f_{Dg} is the fraction of the compound that is dissolved in the aquifer, given by equation A16 in Appendix A.

ζ_I--This attenuation factor is the fraction of the ground water flow from the contaminated catchment that is intercepted by the stream. This can be quite variable, depending on location in the watershed and time of year. If this factor is unknown for a given site, a conservative analysis is suggested in which ζ_I is set to 1.

Q_L--This flow is the average volumetric rate of percolation through the land disposal site, in cubic meters per second, and may be estimated by:

$$Q_L = \frac{\overline{P} \cdot (1-f_R) \cdot A_w}{100 \cdot 86400 \cdot (365.25)} \tag{65}$$

where P is the average annual precipitation rate, in cm/year, $(1-f_R)$ is the fraction of precipitation that leaches through the waste site to ground water, and A_w is the surface area providing water that leaches through the disposal facility, in square meters. If the sides of the disposal facility remain properly lined, and failure occurs through the bottom only, then A_w will be equal to the actual surface area of the disposal facility.

Q_S--This is the average stream flow at the downstream edge of the contaminated plume, in cubic meters per second, and may be estimated by:

$$Q_S = \frac{\overline{P} \cdot (1-\overline{f}_R) \cdot \overline{\zeta}_I \cdot A_S}{100 \cdot 86400 \cdot (365.25)} \tag{66}$$

where $\bar{P}$ is the average annual precipitation rate, in cm/year, $(1-\bar{f}_R)$ is the average fraction of precipitation that leaches through the upper watershed to ground water, $\bar{\zeta}_i$ is the average fraction of ground water flow contributing to stream flow in the upper watershed, and A_S is the surface area of the upper watershed (hydraulically including the contaminated catchment and above). If the average stream flow per unit area is known, then Q_S can be approximated by:

$$Q_S = q_S \cdot A_S \tag{67}$$

where q_S is in units of cubic meters per second per square meter.

Q_U--This is the average stream flow at the upstream edge of the contaminated plume, in cubic meters per second. It may be estimated by:

$$Q_S \cdot \frac{A_S - A_g}{A_S} \tag{68}$$

where A_g is the surface area of the contaminated catchment, diluting the leachate. If A_g is unknown, it may be conservatively estimated as the surface area leaching through the land disposal unit A_w plus the minimum surface area between the facility and the stream.

$$A_g = A_w + X_g \cdot \sqrt{A_w} \tag{69}$$

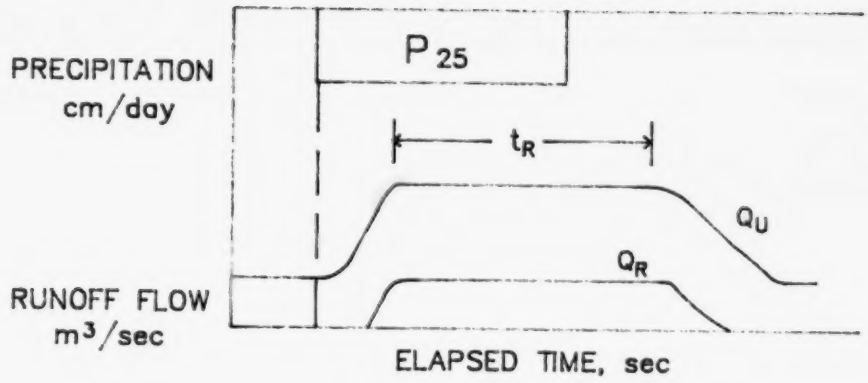
Substituting equations 63, 65, and 66 into 62 and assuming no upstream contamination gives the stream concentration resulting from leachate only:

$$\bar{C}_0 = \exp(-K_g \tau_g) \cdot \frac{A_w}{A_S} \cdot \frac{(1-f_R)}{(1-\bar{f}_R)} \cdot \frac{\zeta_i}{\bar{\zeta}_i} \cdot C_L \tag{71}$$

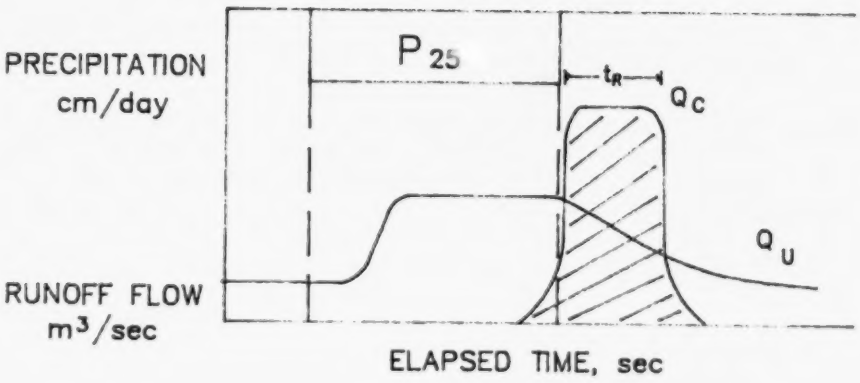
Because clay liners should exhibit lower hydraulic conductivity than natural watersheds, the ratio $(1-f_R)/(1-f_R)$ should be less than 1.0. The ratio $\zeta_i/\bar{\zeta}_i$ could be less than or greater than 1.0, depending on the location of the land disposal site. A conservative analysis could be run assuming equal hydraulic conductivities and the fraction of the contaminated plume intercepted = 1:

$$\bar{C}_0 = \exp(-K_g \tau_g) \cdot \frac{A_w}{\bar{\zeta}_i \cdot A_S} \cdot C_L \tag{72}$$

Storm runoff loading and initial dilution--Contaminants reaching a stream via storm runoff are assumed to enter the stream as a steady load throughout runoff duration t_R (Figure 24). For scenario 2, the time over which the contaminant loading occurs is assumed to be the 1-day duration of the storm. For scenario 3, contaminant loading is assumed to occur for a short duration following the storm. During the runoff event, an initial mixing zone is developed over the runoff discharge area. Within this mixing



(a)



(b)

Figure 24. Precipitation and runoff flows: (a) runoff due to 24-hour precipitation, (b) catastrophic pulse runoff at the end of the 24-hour storm.

zone, dilution of the runoff concentration occurs but is somewhat limited by the magnitude of the runoff flow compared with the stream flow. At the edge of the initial mixing zone (x = 0), it is assumed that the transverse concentration distribution is a Gaussian distribution.

The equations developed in Sections 2.1.1 and 2.1.2 relate contaminant concentrations in the leachate running off the facility with concentrations in runoff at the stream bank, and these with concentrations in stream. Combining equations 9, 10, 23, and 24 gives:

$$C_{0,y} = \zeta_{SR,y} \cdot \frac{Q_R}{Q_{SR}} \cdot C_L + \frac{Q_U}{Q_S} \cdot C_U \qquad (73)$$

where C_L is the leachate concentration, Q_R is the leachate flow running off the facility, Q_{SR} is the runoff flow from the contaminated catchment, Q_U is the upstream flow, C_U the upstream concentration, Q_S is the total down stream flow, and $\zeta_{SR,y}$ is a dilution factor for runoff concentrations describing a lateral, Gaussian distribution across the stream. These terms are discussed below.

$\zeta_{SR,y}$--Runoff entering a stream adds to the stream flow along the bank. It is assumed that stream flow at the bank in the mixing zone is at the runoff concentration, which is diluted laterally according to the Gaussian distribution:

$$\zeta_{SR,y} = \exp(-y^2/2\ \sigma^2) \qquad (74)$$

where y is the lateral distance across the stream and σ is the standard deviation of the distribution, which can be derived from mass balance principles as follows. For the case of no upstream concentrations, the mass flux in the stream at the edge of the mixing zone is equal to the mass flux entering the stream as runoff:

$$\dot{m}_{SR} = \dot{m}_0 \qquad (75)$$

The runoff mass flux is its flow times its concentration:

$$\dot{m}_{SR} = Q_{SR} \cdot C_{SR} \qquad (76)$$

The instream mass flux can be obtained by integrating the lateral concentration distribution over width:

$$\dot{m}_0 = U \cdot d \cdot \int_0^B C_{SR} \cdot \exp(-y^2/2\ \sigma^2)dy \qquad (77)$$

where U is average stream velocity, in meters per second, d is average stream depth, in meters, and B is stream width in meters. Integrating equation 77 and equating it to 76 gives:

$$Q_{SR} \cdot C_{SR} = \sqrt{\pi/2} \cdot U \cdot d \cdot \sigma \cdot C_{SR} \cdot \text{erf}(B/\sigma\ 2) \qquad (78)$$

where erf is the error function, which is equal to 1.0 for $B >> \sigma$. Noting that stream flow Q_S is the product of the mean depth, velocity, and width ($Q_S = UdB$), equation 78 can be solved for σ:

$$\sigma = \frac{B}{\sqrt{\pi/2}} \cdot \frac{Q_{SR}}{Q_S} = 0.798 \cdot B \cdot \frac{Q_{SR}}{Q_S} \qquad (79)$$

Q_R--The leachate flow running off the facility, in cubic meters per second, may be evaluated from:

$$Q_R = \frac{P_{25} \cdot f_R \cdot A_w}{100 \cdot t_R} \qquad (80)$$

where P_{25} is the precipitation for the 25-year recurrence, 24-hour duration storm, in cm, t_R is the time over which contaminant runoff occurs, in sec, f_R is the fraction of the precipitation that runs off the waste site, and A_w is the surface area providing water that leaches through the disposal facility, in square meters. For scenario 2, steady runoff is assumed to occur throughout the storm, and t_R is 86400 seconds. For scenario 3, runoff is assumed to occur over a short period of time following the storm, and t_R is 10^3 - 10^4 seconds.

Q_{SR}--The runoff flow from the contaminated catchment, in cubic meters per second, may be estimated by:

$$Q_{SR} = \frac{P_{25} \cdot f_R \cdot (A_g - A_w)}{100 \cdot t_s} + \frac{P_{25} \cdot f_R \cdot A_w}{100 \cdot t_R} \qquad (81)$$

where t_s is the duration of the storm, or 86400 sec, and A_g is the land area of the contaminated catchment, in square meters, which includes the surface area of the facility A_w plus the surface area between the facility and the stream. Note that for steady runoff throughout the storm, $t_R = t_s$ and equation 81 reduces to:

$$Q_{SR} = \frac{P_{25} \cdot f_R \cdot A_g}{100 \cdot t_s} \qquad (82)$$

For the case of no dilution in overland flow, $A_g = A_w$ and equation 81 reduces to:

$$Q_{SR} = \frac{P_{25} \cdot f_R \cdot A_w}{100 \cdot t_s} = Q_R \qquad (83)$$

Q_U--The stream flow at the upstream edge of the contaminated runoff, in cubic meters per second, may be estimated by

$$Q_U = Q_S^B + \frac{P_{25} \cdot \bar{f}_R \cdot f_R^* \cdot A_U}{100 \cdot t_s} \qquad (84)$$

where $\bar{f}_R$ is the average fraction of the precipitation that runs off the upper watershed, f_R^* is a stream flow recession parameter (0-1) for scenario 3 runoff events that follow a storm, A_U is the surface area of the watershed hydraulically above the contaminated catchment, in square meters, and Q_S^B is the base flow of the upper watershed, in cubic meters per second.

Q_S--The total stream flow at the downstream edge of the mixing zone is the sum of the upstream flow and the runoff flow:

$$Q_S = Q_S^B + \frac{P_{25}}{100} \cdot \left[\frac{\bar{f}_R \cdot A_U}{t_s} + \frac{\bar{f}_R \cdot (A_g - A_w)}{t_s} + \frac{f_R \cdot A_w}{t_R}\right] \qquad (85)$$

Wastewater loading and initial dilution-Contaminants reaching a stream via wastewater discharge are assumed to enter the stream as a steady load of duration t_D. For scenario 4, the time over which the contaminant loading occurs is assumed to be indefinite. For scenario 5, contaminant loading is assumed to occur for a short duration on a regular basis.

During wastewater discharge, an initial mixing zone is developed over the discharge area. Within this mixing zone, dilution of the discharge concentration occurs but is somewhat limited by the magnitude of the discharge flow compared with the stream flow. At the edge of the initial mixing zone ($x = 0$), it is assumed that the transverse concentration distribution is a Gaussian distribution.

The equations developed in Sections 2.1.1 and 2.1.2 relate contaminant concentrations in the industrial waste stream with concentrations in the wastewater effluent, and these with concentrations in stream. Combining equations 14, 15, 26, and 27 gives:

$$C_{0,y} = \zeta_{SD,y} \cdot \zeta_W \cdot \frac{Q_W}{Q_D} \cdot C_W + \frac{Q_U}{Q_S} \cdot C_U \qquad (86)$$

where C_W is the industrial waste concentration, Q_W is the industrial waste flow, Q_D is the wastewater effluent flow, ζ_W is the treatment plant mass attenuation factor, Q_U is the upstream flow, C_U is the upstream concentration, Q_S is the total downstream flow, and $\zeta_{SD,y}$ is a dilution factor for effluent concentrations describing a lateral, Gaussian distribution across the stream. These terms are discussed below.

$\zeta_{SD,y}$--Wastewater effluent entering a stream adds to the stream flow at a point near the bank. It is assumed that stream flow at the bank in the

mixing zone is at the effluent concentration, which is diluted laterally according to the Gaussian distribution:

$$\zeta_{SD,y} = \exp(-y^2/2\sigma^2) \tag{87}$$

where y is lateral distance across the stream and σ is the standard deviation of the distribution. This parameter can be derived following equations 75-79, substituting $\dot{m}_D$ for $\dot{m}_{SR}$ and Q_D for Q_{SR} to give:

$$\sigma = \frac{B}{\sqrt{\pi/2}} \cdot \frac{Q_D}{Q_S} = 0.798 \cdot B \cdot \frac{Q_D}{Q_S} \tag{88}$$

ζ_W--The treatment plant mass attenuation factor accounts for the effects of sorption and settling, volatilization, and bacterial degradation. No general equation is developed here for calculating ζ_W. If no measured or independently estimated value is specified by the user, ζ_W defaults to 1 and mass is conserved through the treatment plant.

Q_W--The flow rate for the industrial waste stream, in cubic meters per second, must be specified by the user. If total loading m_W and concentration C_W are known, then Q_W can be calculated by:

$$Q_W = \frac{m_W}{C_W \cdot t_D} \tag{89}$$

where m_W is expressed in grams, C_W is expressed in mg/L (or grams per cubic meter), and t_D is expressed in seconds.

Q_D--The flow rate of the wastewater treatment effluent, in cubic meters per second, must be specified by the user.

Q_U--The upstream flow, in cubic meters per second, can be specified by the user. If unknown, an average flow condition can be calculated:

$$Q_U = q_S \cdot A_S \tag{90}$$

where q_S is the average stream flow per unit area, in cubic meters per second per square meter, and A_S is the surface area of the watershed above the discharge, in square meters.

Q_S--The stream flow at the point of mixing is the sum of the upstream flow and the effluent flow:

$$Q_S = Q_U + Q_D \tag{91}$$

2.3.2 Transport and Transformation in Stream--

Following initial dilution in the stream, contaminants at peak concentration, C_0, are routed downstream under the combined influence of advection,

longitudinal and lateral dispersion, degradation and sorption. The concentration at downstream distance x from the edge of the initial mixing zone is C_x and is related to C_0 via equations 28 and 29, in which ζ_x is the attenuation factor for transport in surface water. The expressions for ζ_x can be obtained from analytical solutions of the transient two-dimensional transport equation. Two cases corresponding to continuous loading and pulse loading of contaminants are considered.

Stream transport below continuous ground water loading--The laterally averaged concentration at the downstream edge of the ground water plume (x = 0) is $\overline{C}_0$ (see Figure 24). At a given measurement point located at distance x from the edge of the mixing zone (Figure 6a), the concentration will quickly reach a steady-state value under base flow conditions. The steady-state, laterally averaged solution for concentrations at the measurement point is given by:

$$\zeta_x = e^{-K.\tau} \tag{92}$$

where: $\tau = x/U$ (93)

K = decay rate constant, sec-1

U = mean downstream velocity, m/sec

For calculating bioconcentration in scenario 1B or chronic toxicity in scenario 1C, we assume that the fish reside continuously in the upstream area where the effect of degradation is insignificant (x = 0). Therefore in this case ζ_x is 1, and C_x becomes $\overline{C}_0$.

Stream transport below pulse runoff loading--Pulse runoff loading produces a lateral concentration profile that is a Gaussian distribution characterized (at x = 0) by a maximum C_R and a standard deviation of σ over the contaminant loading period t_R (see Figure 6b). Downstream transport will be accompanied by lateral mixing until the contaminants are evenly dispersed across the stream. The concentrations at a given measurement point, x, will increase from zero to a relatively steady value between times (x/U) and (x/U + t_R). At subsequent times, the concentrations will decrease gradually and become zero as the contaminant slug passes through the measurement point. The general analytical solution for transient, two-dimensional transport from a Gaussian pulse source is presented in Appendix B. This solution may be written as:

$$\zeta_{x,y} = [C_f^*(x,y,t) + \sum_{i=1}^{\infty} C_{fi}^*(x,y,t) - C_f^*(x,y,t-t_R) - \sum_{i=1}^{\infty} C_{fi}^*(x,y,t-t_R)] \tag{94}$$

where:

$$C_f^*(x,y,t) = \frac{\sigma x \exp(U/2E_x)}{(2\pi E_x)^{1/2}} \cdot I \qquad (95)$$

$$I = \int_0^t \frac{\exp\left(-\frac{x^2}{4E_x\tau} - \frac{y^2}{4E_y\tau + 2\sigma^2} - \frac{U^2\tau}{4E_x} - K\tau\right) d\tau}{\tau^{3/2}(2\sigma^2+4E_y\tau)^{1/2}} \qquad (96)$$

$$C_{fi}^* = C_f^*(x,\ 2Bi + 6\cos(i\pi),\ t) \qquad (97)$$

E_x = longitudinal dispersion coefficient, m^2/sec

E_y = lateral dispersion coefficient, m^2/sec

The infinite series in equation 94 is evaluated in a computer subroutine using finite sums of N terms, where N corresponds to the number of image sources described in Appendix B. Good convergence is obtained with N <10. The integral I is evaluated numerically using Gaussian quadrature.

Stream transport below pulse discharge loading--Pulse discharge loading produces a lateral concentration profile that is a Gaussian distribution characterized (at x = 0) by a maximum C_0 and a standard deviation of σ over the contaminant loading period t_D. Downstream transport will be accompanied by lateral mixing until the contaminants are evenly dispersed across the stream. The concentrations at a given measurement point, x, will increase from zero to a relatively steady value between times (x/U) and (x/U + t_D). At subsequent times, the concentrations will decrease gradually and become zero as the contaminant slug passes through the measurement point. The general analytical solution for transient, two-dimensional transport from a Gaussian pulse source is presented in Appendix B. This solution is given by equations 94-97 (with t_D substituted for t_R in equation 94).

2.3.3 Contaminant Delivery to Drinking Water and Fish--

At a distance x downstream, contaminants at concentration C_x may be taken into a drinking water plant or exposed to aquatic organisms, including fish. The drinking water concentration C_{DW}, the aquatic exposure concentration C_{EXP}, and the fish body concentration C_F must be calculated from C_x.

Delivery of contaminant through drinking water--Drinking water plants take in raw water at a distance x downstream from the point of discharge. As a minimum requirement, it is assumed that in any drinking water plant, the raw water having contaminant concentration C_x is treated by allowing suspended solids and adsorbed chemical to settle out. This leads to a reduction of concentration from C_x to C_{DW}. The relationship between C_{DW} and C_x is given by equation 13 with ζ_{DW} being the dilution factor corresponding to the fraction

of the compound that is dissolved, f_D. The expression for f_D is developed in Appendix A. This may be written as:

$$\zeta_{DW} = f_D = \frac{1}{1 + 0.41\ K_{ow} \cdot f_{oc} \cdot S \cdot 10^{-6}} \qquad (98)$$

where:

K_{OW} = octanol-water partition coefficient, ℓ_{oct}/ℓ_{water}

f_{oc} = organic carbon fraction of sediment

S = sediment concentration, mg/l

Delivery of contaminants to aquatic organisms--Aquatic organisms are exposed to contaminants at a distance x downstream from the point of discharge. Only dissolved species of a compound cross fish membranes and cause internal exposure. There is some evidence, however, that suspended solids with sorbed species can enhance the rate of uptake and thus internal exposure of a compound. The CCC set to protect against chronic toxic effects is generally referenced to the total concentration of a compound. Therefore, ζ_{EXP} is set to 1 and C_{EXP} is equated to C_x.

Delivery of contaminants through fish to humans--Dissolved neutral organic compounds in the water can be taken up by fish through exchange across the gill and gut membranes and through the skin. Contaminated food can be ingested, resulting in further exchange of compounds across the gut membrane. Concentration levels in the fish will rise until the activity of the compound in the blood equals the activity of the compound in the water. This condition represents chemical equilibrium. Further uptake of the compound resulting in higher blood concentrations will lead to net exchange out of the fish through the gill, gut, kidney, and skin. Consequently, any chemical buildup above the equilibrium level is controlled by the relative rates of ingestion, metabolism, and exchange. There is some evidence that active transport across the gut can cause the equilibrium concentration to be exceeded:

$$C_B = K_{FC}\ f_D\ C_x \qquad (99)$$

where C_B is the dissolved concentration in the blood, mg/L, f_D is the fraction of chemical dissolved, and K_{FC} is the food chain bioaccumulation factor, expected to range from 2-3.

If the fish is exposed to steady aqueous concentrations over a long period of time, the distribution of the compound within the various fish tissues will equilibrate, so that:

$$C_\ell = K_\ell \cdot C_B \qquad (100)$$

and

$$C_{n\ell} = K_{n\ell} \cdot C_B \quad (101)$$

where:

C_ℓ = lipid (or fat) biomass concentration, mg/kg

K_ℓ = lipid phase partition coefficient, L/kg

$C_{n\ell}$ = non-lipid (blood, muscle) biomass concentration, mg/kg

$K_{n\ell}$ = non-lipid partition coefficient, L/kg

The average whole fish concentration C_F (mg/kg) is the weighted sum of the tissue concentrations:

$$C_F = f_\ell \cdot C_\ell + (1-f_\ell)\, C_{n\ell} \quad (102)$$

where f_ℓ = fraction of biomass that is lipid. Substituting equation 99 and 100 into 101 gives:

$$C_F = K_{FC}\, K_F\, f_D\, C_x \quad (103)$$

where K_F is the entire fish partition coefficient, or bioconcentration factor given by:

$$K_F = K_\ell\, f_\ell + K_{n\ell}\, (1-f_\ell) \quad (104)$$

Equation 103 reduces to equation 32 provided that the parameter ζ_F is defined as:

$$\zeta_F = K_{FC} \cdot K_F \cdot f_D \quad (100)$$

Note that, unlike the dilution factors, ζ_F is not dimensionless. The unit for ζ_F is L/kg. For strongly hydrophobic compounds, lipid storage dominates K_F. The lipid phase partition coefficient can be replaced by the octonal-water partition coefficient, so that, approximately:

$$K_F = K_{OW} \cdot f_\ell \quad (106)$$

For less hydrophobic compounds, $K_{n\ell}$ may contribute significantly to K_F. Non-lipid tissue is composed primarily of water, along with protein and carbohydrates. Assuming that partitioning to non-lipids is always less than or equal to 1% of the partitioning to lipids, a conservative estimate of K_F is approximately (R.R. Lassiter, USEPA, personal communication):

$$K_F = K_{OW} \cdot (f_\ell + 0.01) \quad (107)$$

For highly polar compounds and metals, the bioconcentration factor K_F can not be estimated from the octanol-water partition coefficient and lipid fraction. In this case, observed field or experimental values of K_F must be used directly.

SECTION 3

USER'S MANUAL

SARAH is an interactive model. The computer program, through a series of menus and questions, will automatically build a data set or default to predefined values at the user's discretion.

3.1 EXPLANATION OF MENUS

SARAH interactively allows the user a choice of chemical release and exposure scenarios. For each scenario, the user can default to predefined input values or enter site-specific input values. Many calculations can be performed for each scenario by systematically varying selected input values.

3.1.1 Selection of Scenarios

The user must first define a complete problem to analyze, including the loading and the exposure scenarios. The first menu allows the user to specify one of five possible loading scenarios, or to exit the program:

```
(1)  Steady ground water loading
(2)  Storm runoff loading
(3)  Catastrophic pulse loading
(4)  Continuous discharge loading
(5)  Batch discharge loading
(6)  Exit
```

The second menu allows the user to specify one of three possible exposure scenarios:

```
(1)  Human exposure through drinking water
(2)  Human exposure through fish consumption
(3)  Toxicity to aquatic organisms
```

If Loading Scenario 2 or 3 was previously selected, then the specification of Exposure Scenario 2 or 3 results in a return to the Loading Menu, because human exposure through fish and direct aquatic exposure by runoff loading are not implemented.

3.1.2 Operation of Model

Following specification of the problem, the user is supplied the following Operation Menu:

```
(1)  Use default input values
(2)  Display default input values
(3)  Enter sets of input values
(4)  Display current input values
(5)  Enter selected input values
(6)  Run program
(7)  Return to main menu
```

Before the user may run the program, a data set must be specified using choices: 1, 3, or 5. To use the default values, select choice 1 and specify one of three options in the Default Input Menu:

```
(1)  Use default input values #1
(2)  Use default input values #2
(3)  Use default input values #3
```

The values and description of each default selection (1, 2, or 3) are listed in Section 3.3.

After default input values are selected, the model will return to the Operation Menu.

If choice 3 is selected, the user may enter sets of input values grouped by subject matter. Selections can be made from the Subject Matter Menu:

```
          Enter all input values

          (1) Hydrological
A<S       A<W

          (2) Stream Env.
S     f<OC    f<l

          (3) Compound
K<ow      k<HA    k<HN    k<HB

          (4) Loading/Exposure
C'<ADI

          (6) Ground water
VWG       THETAG    TG    FOCG    TRG    XG    PHG

          Enter choice (1-6, 0 to stop)>
```

If subject 1 is selected, the model will request the user to define the new value of A<s, then the new value of A<w. After every variable in the selected subject has been defined by the user, the model will return to the Subject Matter Menu and allow the user to choose another subject. The user may return to the Operation Menu at any time by entering a zero.

If choice 5 is selected, the user may enter individual input values. Selections can be made from the Selected Input Menu:

```
          Enter Selected Input Values

                Hydrological
(1) A<s   (2) A<w

                Stream Env.
(3) S     (4) f<oc          (5) f<l

                Compound
(6) K<ox (7) k<HA    (8) k<HN    (9) k<HB

                Loading/Exposure
(10) C'<ADI

                Ground water
(11) VWG    (12) THETAG    (13) TG    (14) FOCG
(15) TRG    (16) XG    (17) PHG

          Enter choice (1-17, 0 to stop) >
```

If variable 3 is selected, the model will request a value for S. After the user defines S, the model will return to the Selected Input Menu and

allow the user to select another variable. The user may return to the Operation Menu at any time by entering a zero.

At this point, the user may select to run the program by entering (6). Output variables and intermediate variable values will be printed on the screen. The user can return to the Operation Menu following each "Run" command by entering (7).

3.2 SCENARIO VARIABLES

Numerous equations have been presented that together describe leachate loading, dilution, instream transport and transformation, and exposure to humans through drinking water and fish consumption. The many variables are categorized by scenario, then grouped into those describing the watershed hydrology, the stream and ground water environments, the compound properties, and the loading/exposure scenario.

The number of potential input variables may appear to make practical application of this analysis difficult. Fortunately, many of these inputs can be estimated from other more readily available variables. Furthermore, many terms in the equations can be ignored for a more conservative analyses.

The input variables for each scenario are listed in the following tables. These tables are designed to give the user the choice of a conservative analyses with a minimum set of data, more complete analyses with a recommended set of data, and "full equation" analyses with an optional set of data.

The steps for calculating an allowable leachate concentration for Scenario 1 are summarized in Table 2. Input variables are given in Table 3. The calculations and input data for Scenarios 2 and 3 are summarized in Tables 4 and 5. Calculations and input data for Scenario 4 and 5 are summarized in Tables 6 and 7.

3.3 DEFAULT VALUES

SARAH contains three default data sets. A user may use any one of the three as is, alter variables in any of the three, or build a totally new data set.

The first data set represents a small, flat watershed containing a large land disposal facility and a slow, shallow stream. The second set represents a small, moderately steep watershed containing a medium-sized land disposal facility and a faster, deeper stream. The third set reflects a large, steep watershed containing a large land disposal facility and a fast, shallow stream. All three contain a small wastewater treatment facility that receives a steady industrial waste stream. The input values for each variable are listed in Table 8.

TABLE 2. CALCULATIONS FOR SCENARIO 1

Step	Calculate	Explanation (and Equations)
1	τ_g(TAUG)	Travel time of contaminant from land disposal facility to stream, years (A17, A16, 64).
2	K_g(KHG)	First-order rate coefficient for hydrolysis in ground water, years^{-1} (A23, A25).
3	ζ_H(RH)	Mass attenuation factor in ground water (63).
4	ζ_{Sg}(RSG)	Concentration dilution factor in ground water and stream (65, 66, 67).
5	ζ_{SU}(RSU)	Concentration dilution factor for upstream contaminants (69, 68, Q_U/Q_S).
6	ζ(TAU)	Travel time of contaminant downstream, seconds (A4, 93).
7	K(KK)	First order rate coefficient for hydrolysis and volatilization in stream, seconds^{-1} (A15, A22, A24, A30, A29, A34, (A32, A33, or A35), A27, A28, A26, A19).
8	ζ_x(RX)	Concentration reduction factor for downstream transformations (92).
9	ζ_{DW}(RDW)	Drinking water treatment reduction factor (A15, 98).
10	ζ_F(RF)	Fish bioaccumulation factor (107, A15, 100).
11	ζ_F(RG)	Concentration dilution factor due to transport in ground water ($=\zeta_H\ \zeta_i\ Q_L/Q_S$) (63, 65, 66).
12	C_L(CL)	Acceptable leachate concentration, mg/L (Drinking Water: ζ_{SU}, 92, 98, ζ_g, 67; Aquatic Organisms: ζ_{SU}, ζ_g, 67; Fish Accumulation: ζ_{SU}, 100, ζ_g, 67).

TABLE 3. INPUT VARIABLES FOR SCENARIO 1

Input Variable	Value Range	Conservative	Recommended	Optional
Hydrological				
A_W	$10^4 - 10^6$	X		
A_g	$10^4 - 10^6$			X
A_S	$10^7 - 10^9$	X		
$\overline{P}$	10 - 200		X	
f_R	0.1 - 0.5		X	
$\overline{f}_R$	0.1 - 0.5		X	
ζ_i	0.1 - 1.0		X	
$\overline{\zeta}_i$	0.1 - 1.0		X	
q_S	$10^{-9} - 10^{-8}$			X
Q_S	$10^{-2} - 10$			X
Ground water				
X_g	$10 - 10^3$		X	
V_g	$1 - 10^5$		X	
θ_g	0.3 - 0.5		X	
f_{ocg}	0.001-0.10		X	
T_g	10 - 20		X	
pH_g	5 - 8		X	

TABLE 3. INPUT VARIABLES FOR SCENARIO 1 (Continued)

Input Variable	Value Range	Conservative	Recommended	Optional
Stream Env.				
C_U	--			X
U	0.1 - 2		X	
d_o	0.1 - 3		X	
s	10^{-4} - 10^{-2}			X
n	0.02 - 0.08			X
f_{oc}	0.01 - 0.10		X	
S	10 - 50		X	
T	5 - 30		X	
$W(W_z, z)$	0 - 10			X
pH	5 - 8			X
Compound				
K_{ow}	10 - 10^7	X		
k_{HA}	0 - 10^{-1}		X	
k_{HN}	0 - 10^{-5}		X	
k_{HB}	0 - 10^{-1}		X	
T_R	15 - 25			X
MW	10 - 10^3			X
H	10^{-7} - 10^{-1}			X

TABLE 3. INPUT VARIABLES FOR SCENARIO 1 (Continued)

Input Variable	Value Range	Conservative	Recommended	Optional
Exposure				
C'_{ADI}	--	X		
C_{ADI}	--	X		
K_{FX}	1 - 3		X	
f_{ℓ}	0.01 - 0.25	X		
X	0 - 5000			X
CCC	--	X		

TABLE 4. CALCULATIONS FOR SCENARIOS 2, 3

Step	Calculate	Explanation (and Equations)
1	ζ_R(RRU)	Concentration dilution factor in surface runoff (80, 81, 10).
2	$\zeta_{SR,y}$(RSRY)	Concentration dilution factor across stream at point of mixing (A3, 84, 85, A4, A5, A7, 79, 74).
3	ζ_{SU}(RSU)	Concentration dilution factor for upstream contaminants (27).
4	τ(TAU)	Travel time of contaminant downstream, seconds (A4, 93).
5	K(KK)	First order rate coefficient for hydrolysis and volatilization in stream, seconds^{-1} (A15, A22, A24, A30, A29, A34, (A32, A33, or A35), A31, A27, A28, A26, A19).
6	$\zeta_{x,y}$(RXY)	Concentration reduction factor for downstream transformation (A8, A9, A10, 96, 95, 97, 94).
7	ζ_{DW}(RDW)	Drinking water treatment reduction factor (A15, 98).
8	C_L(CL)	Acceptable leachate concentration, mg/L (27, 10, 74, 98, 94, 46).

TABLE 5. INPUT VARIABLES FOR SCENARIO 2 AND 3

Input Variable	Value Range	Conservative	Recommended	Optional
Hydrological				
A_W	$10^4 - 10^6$	X		
A_g	$10^4 - 10^6$			X
A_U	$10^7 - 10^9$	X		
P_{25}	10 - 15	X		
f_R	0.1 - 0.5		X	
$\overline{f}_R$	0.1 - 0.5		X	
f_R^*	0 - 1			X
q_s	$10^{-9} - 10^{-8}$	X		
Q_S^B	$10^{-2} - 10$			X
t_s	$10^3 - 10^6$		X	
t_R	$10^3 - 10^6$			X
Stream Env.				
C_U	--			X
d_o	0.1 - 3	X		
s	$10^{-4} - 10^{-2}$		X	
n	0.02 - 0.08		X	
b	0.02 - 0.5		X	
f	0.2 - 0.7		X	
f_{oc}	0.01 - 0.10	X		
S	$10^{-4} - 10^{-2}$	X		

TABLE 5. INPUT VARIABLES FOR SCENARIO 2 AND 3 (Continued)

Input Variable	Value Range	Conservative	Recommended	Optional
T	5 - 30			X
W	0 - 10			X
pH	5 - 8			X
E_x	1 - 10			X
E_y	10^{-2} - 10^{-1}			X
Compound				
K_{ow}	10 - 10^7	X		
k_{HA}	0 - 10^{-1}			X
k_{HN}	0 - 10^{-5}			X
k_{HB}	0 - 10^{-1}			X
T_R	15 - 25			X
MW	10 - 10^3			X
H	10^{-7} - 10^{-1}			X
Exposure				
C'_{ADI}	--	X		
C_{ADI}	--	X		
K_{FC}	1 - 3		X	
F_ℓ	0.01 - 0.25	X		
X	0 - 5000	X		
y	0 - B		X	
CCC	---	X		

TABLE 6. CALCULATIONS FOR SCENARIOS 4, 5

Step	Calculate	Explanation (and Equations)
1	ζ_D(RWD)	Concentration reduction factor in wastewater treatment (89 (i.e., 89, 15)).
2	$\zeta_{SR,y}$(RSRY)	Concentration dilution factor across stream at point of mixing (90, 91, A4, A5, A7, 88, 74).
3	ζ_{SU}(RSU)	Concentration reduction factor for upstream contaminants (27).
4	τ(TAU)	Travel time of contaminant downstream, seconds (A4, 93).
5	K(KK)	First order rate coefficient for hydrolysis and volatilization in stream, seconds^{-1} (A15, A22, A24, A30, A29, A34, (A32, A33, or A35), A27, A28, A26, A19).
6	$\zeta_{x,y}$(RXY)	Concentration reduction factor for downstream transformation (A8, A9, A10, 96, 95, 97, 94).
7	ζ_{DW}(RDW)	Drinking water treatment reduction factor (A15, 98).
8	ζ_F(RF)	Fish bioaccumulation factor (107, A15, 100).
9	C_W(CW)	Acceptable industrial waste concentration, mg/L (50, 57, 53, 41, 56, or 61).

TABLE 7. INPUT VARIABLES FOR SCENARIO 4 AND 5

Input Variable	Value Range	Conservative	Recommended	Optional
Hydrological				
A_w	10^4 - 10^6	X		
A_g	10^4 - 10^6			X
A_s	10^7 - 10^9	X		
P_{25}	10 - 15	X		
f_R	0.1 - 0.5		X	
$\overline{f}_R$	0.1 - 0.5		X	
f_R^*	0 - 1			X
q_s	10^{-9} - 10^{-8}	X		
Q_S^B	10^{-2} - 10			X
t_s	10^3 - 10^6		X	
t_R	10^3 - 10^6			X
Stream Environment				
C_U	--			X
d_o	0.1 - 3	X		
s	10^{-4} - 10^{-2}		X	
n	0.02 - 0.08		X	
b	0.02 - 0.5		X	
f	0.2 - 0.7		X	
f_{oc}	0.01 - 0.10	X		
S	10^{-4} - 10^{-2}	X		

TABLE 7. INPUT VARIABLES FOR SCENARIO 4 AND 5 (Continued)

Input Variable	Value Range	Conservative	Recommended	Optional
T	5 - 30			X
W	0 - 10			X
pH	5 - 8			X
E_x	1 - 10			X
E_y	10^{-2} - 10^{-1}			X
Compound				
K_{ow}	10 - 10^7	X		
k_{HA}	0 - 10^{-1}			X
k_{HN}	0 - 10^{-1}			X
k_{HB}	0 - 10^{-1}			X
T_R	15 - 25			X
MW	10 - 10^3			X
H	10^{-7} - 10^{-1}			X
Loading and Exposure				
C'_{ADI}	--	X		
C_{ADI}	--	X		
K_{FC}	1 - 3		X	
f_ℓ	0.01 - 0.25	X		
X	0 - 5000	X		
y	0 - B		X	
CCC	--	X		

TABLE 7. INPUT VARIABLES FOR SCENARIO 4 AND 5 (Continued)

Input Variable	Value Range	Conservative	Recommended	Optional
ζ_w	0-1			X
t_D	10^3-10^6		X	
Q_w	10^{-3}-1			
Q_D	0.004-12			

TABLE 8. DEFAULT VALUES FOR DATA SETS #1, #2, AND #3

	Hydrology and Hydrogeometry #1	#2	#3
AS	1.0D7	1.0D7	1.0D8
AW	1.0D6	1.0D5	1.0D6
P25	12.5D0	15.0D0	10.0D0
RS	0.4D0	0.4D0	0.4D0
RW	0.5D0	0.4D0	0.3D0
BEXP	0.23D0	0.40D0	0.55D0
FEXP	0.42D0	0.20D0	0.30D0
Q	0.5D-8	1.0D-8	1.0D-9
S	9.0D-5	1.0D-3	5.0D-3
DO	0.3D0	1.0D0	0.2D0
DD	1.0D0	1.0D0	1.0D0
NN	0.04D0	0.02D0	0.06D0
FR	1.00D0	0.6000	1.00D0
FL	0.3D0	0.2D0	0.1D0
TS	8.64D4	8.64D4	8.64D4
TL	7.2D3	3.6D3	1.8D3
	Ground water		
VWG	10.0D0	150.0D0	900.0D0
THETAG	0.5D0	0.4D0	0.3D0
TG	20.0D0	15.0D0	10.0D0
FOCG	0.01D0	0.005D0	0.001D0
TRG	25.0D0	25.0D0	25.0D0
XG	150.0D0	150.0D0	150.0D0
PHG	5.0D0	6.6D0	8.0D0

TABLE 8. DEFAULT VALUES FOR DATA SETS #1, #2, AND #3 (Continued)

	Hydrology and Hydrogeometry		
	#1	#2	#3
	Environmental		
T	20.0D0	25.0D0	15.0D0
SS	10.0D0	50.0D0	100.0D0
PH	7.0D0	7.5D0	6.5D0
FOC	0.05D0	0.1D0	0.01D0
WW	2.0D0	4.0D0	1.0D0
Z	10.0D0	10.0D0	10.0D0
	Chemical		
K	0.0D0	0.0D0	0.0D0
KHA	0.0D0	0.0D0	0.0D0
KHB	0.0D0	0.0D0	0.0D0
KHN	0.0D0	0.0D0	0.0D0
HH	1.0D-7	1.0D-7	1.0D-7
MW	1.0D3	1.0D3	1.0D3
KOW	1.0D3	1.0D4	1.0D5
	Loading/Exposure		
X	1.0D3	1.0D3	1.0D3
Y	0.0D0	0.0D0	0.0D0
CADI	1.0D0	1.0D0	1.0D0
CPADI	1.0D0	1.0D0	1.0D0
RW	1.0D0	1.0D0	1.0D0
TD	8.6D4	8.6D4	8.6D4
QWI	4.0D-3	4.0D-3	1.0D-1
QD	4.0D-3	1.0D-3	2.0D-1

Note: D5 = 10^5

SECTION 4

PROGRAMMER'S MANUAL

This section contains information to familiarize the user with the programming aspects and operational characteristics of the model. The hardware and software section contains information on program compilation and a description of the files on the distribution tape with a listing of required disk space. The installation and implementation section lists commands for mounting the tape and running the model. The program description section describes the input/output device, the common block and each subroutine.

4.1 HARDWARE AND SOFTWARE REQUIREMENTS

SARAH was compiled under the PDP IAS FORTRAN 77 and the VAX VMS FORTRAN.

The files contained on the distribution tape (for a VAX system) are: SARAH.CMN, SARAH.COM, SARAH.FOR, and SARAH.EXE. The following is a description of each file and the disk space required by each.

File	Description	Number of Blocks (512 byte records)
SARAH.CMN	Include file with common blocks	3
SARAH.COM	Command file for compiling and linking source code	1
SARAH.FOR	FORTRAN source code	178
SARAH.EXE	Executable image	96

4.2 VAX INSTALLATION AND IMPLEMENTATION

The following steps and commands are required to install SARAH on a VAX system:

Description	Command
Mounting tape	MOU/NOASSIST/OVERRIDE=OWNER-ID MSAØ: SARAH
Setting directory default	SET DEF DBAØ:[xxx.yyy]
Copying contents	COPY MSAØ:*.*;*DBAØ:[xxx.yyy]
Verifying files were copied	DIR
Dismounting the tape	DISMOUNT MSAØ:
Compiling code (if necessary)	@ SARAH.COM

The VAX command file (SARAH.COM) deletes the previous executable file, compiles the source code SARAH.FOR to create the object file SARAH.OBJ, links the object file to the executable file (SARAH.EXE) which is used to run the model, cleans out account, and renames all versions to 1. The following is a listing of SARAH.COM:

```
$ SET VERIFY
$!              SARAH.COM
$ ON WARNING THEN CONTINUE
$ DEL SARAH.EXE;*
$ FORTRAN SARAH
$ LINK SARAH
$ PURGE SARAH.*
$ DEL SARAH.OBJ;*
$ REN SARAH.*;* SARAH.*;1
$ EXIT
```

4.3 PROGRAM DESCRIPTION

4.3.1 Input/Output Units

Because SARAH is an interactive program, all variables and results are defined and printed onto the terminal screen (IUNIT5). To run the model type: RUN SARAH.

4.3.2 Common Block

SARAH uses a common block (SARAH.CMN) to transfer data between subroutines. This common block consists of real, integer (both are double precision), or character specifications for variables. The common block is divided into 12 subsections according to subject matter. The following is a listing and a short definition of each subsection.

Subsection	Definition
OTHERR	Real variables
OTHERC	Character variables
OTHERI	Integer variables
CALCV	Variables used in calculations
HYDR	Hydrology and hydrogeometry variables
STREAM	Environmental variables
CHEM	Chemical variables
LOADEX	Loading/exposure variables
CLEARS	Variables used to clear terminal screen
IO	Input/output variables
CONST	Constant variables
GWATER	Groundwater variables

Further definitions for each variable may be found in Appendix A.

4.3.3 Common Block Listing

```
C                                   SARAH.CMN
C
      IMPLICIT REAL*8(A-H,O-Z)
      INTEGER*2 IMAGE,IUNIT5,M1,m2,M3,M4,M5,M7,N,CC,M51,M61,M71,
     X          IERR,M8,M1A
      CHARACTER ANS,CLR1(10),CLR2(10),HOLDIT,MENU,SLAB(3)*40,
     X          TERM
      REAL*8 K20,KH,KK,KO2,KV,K,KHA,KHB,KHN,KOW,MW,NN,DATA(30),
     X          KF,FD,DDP,CPAD1,FL,NU,KHG,KHGO
C
      COMMON/OTHERR/ DATA
C
      COMMON/OTHERC/ ANS,CLR1,CLR2,HOLDIT,MENU,SLAB
C
      COMMON/OTHERI/ IMAGE,M1,M2,M3,M4,M5,M7,N,CC,M51,M61,M71,
     X          IERR,M8,M1A
C
C
      COMMON/CALCV/ A,ALPHA,ARG1,ARG2,B1,B2,BETA,
     X          DELTA,DPRIME,E,E1,EQ1,EQ2,EQ3,EQ4,
```

```
     X                F,H,
     X                OMEGA,R,RDATA,RL,
     X                TERM1,TERM2,TR,
     X                USV,W,WAT,WZ,XPRIME,YY,FL,DDP,KF
C
      COMMON/HYDR/  AS,AW,BBO,BB,D,DO,QQO,QQ,P25,Q,RS,RW,S,
     X                BEXP,FEXP,UO,U,NN,FR
C
      COMMON/STREAM/ B,DD,DF,EX,EY,FOC,PH,POH,SS,T,TK,WW,WIO,QW
C
      COMMON/CHEM/ HH,K,KHA,KHB,KHN,KOW,MW,K2O,KO2,KV,KH,FS,FD,KK
C
      COMMON/LOADEX/ CADI,CL,TAU,TSD,TL,X,Y,Z,CPADI,SIGMA
C
      COMMON/CLEARS/ TERM
C
      COMMON/IO/ IUNIT5
C
      COMMON/CONST/ RGAS,G
C
      COMMON/GWATER/ VWG,THETAG,RHOBG,TG,TRG,FOCG,XG,PHG,POHG,
     X               FDG,FSG,KHGO,KGH,RTG,VSOLG,TAUG,RG
```

4.3.4 Subroutine Descriptions

Figure 25 is a flow chart of SARAH illustrating the functional relationships among the subroutines. (Note: SARAH has no overlay structure.) The following is a brief explantion of each subroutine function.

Description	Function
SARAH.FOR (main program)	Calls first menu program DWM1.FOR.
CLSCR.FOR	Subroutine used to clear terminal screen.
DWM1.FOR	Subroutine to display menu of potential contaminant sources.
DWM2.FOR	Subroutine to display menu of default values use, display default values, enter input values, display input values, enter selected input values, run program, or return to main menu.
DWM3.FOR	Subroutine to display menu for default value sets #1, #2, or #3 menu.
DWM4.FOR	Subroutine to display choice of displaying selected default values.

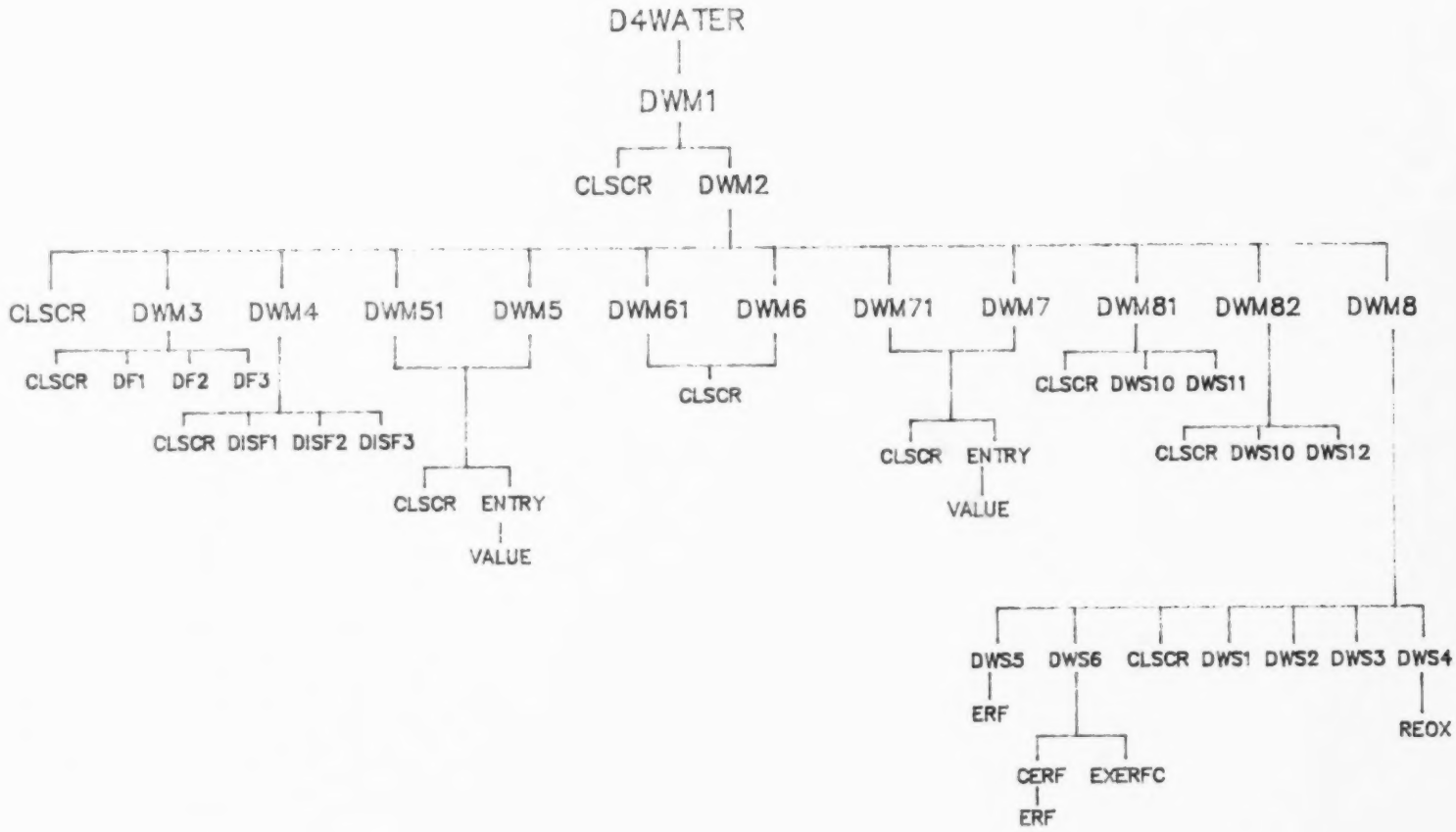


Figure 25. Reltionships in SARAH subroutines.

DWM5.FOR	Subroutine used for entry of all input values when potential contaminant source is not steady ground water loading.
DWM51.FOR	Subroutine used for entry of all input values when potential contaminant source is steady ground water loading.
DWM6.FOR	Subroutine used to display all input values when potential contaminant source is not steady ground water loading.
DWM61.FOR	Subroutine used to display all input values when potential contaminant source is steady ground water loading.
DWM7.FOR	Subroutine used for entry of selected input values when potential contaminant source is not steady ground water loading.
DWM71.FOR	Subroutine used for entry of selected input values when potential contaminant source is steady ground water loading.
DWM8.FOR	Subroutine that calls the set of calculation programs when potential contaminant source is not steady ground water loading.
DWM81.FOR	Subroutine that calls the set of calculation programs when potential contaminant source is steady ground water loading and potential effect of release is human exposure through fish consumption.
DWM82.FOR	Subroutine that calls the set of calculation programs when potential contaminant is steady ground water loading and potential effect of release is toxicity to aquatic organisms.
DWS1.FOR	Subroutine used by Scenario 2/3 for advection calculations.
DWS2.FOR	Subroutine used by Scenariio 2/3 for stream transport calculations.
DWS3.FOR	Subroutine used by Scenario 2/3 for dispersion calculations.
DWS4.FOR	Subroutine used by Scenario 2/3 for chemical transformation calculations.

DWS5.FOR	Subroutine used by Scenario 2/3 for rectangular distribution calculations.
DWS6.FOR	Subroutine with analytical solution to the transient two-dimensional ground water pollution model.
DWS10.FOR	Subroutine used by Scenario 1 for calculations.
DWS11.FOR	Subroutine used by Scenario 1B for calculations.
DWS12.FOR	Subroutine used by Scenario 1C for calculations.
CERF.FOR	Subroutine used to compute an error function with a complex argument.
DF1.FOR	Subroutine with 1st set of 3 sets of default values assigned to variables. Subroutine that defines values to the first set of 3 sets of default variables.
DF2.FOR	Subroutine that defines values to the second set of 3 sets of default.
DF3.FOR	Subroutine that defines values to the third set of 3 sets of default variables.
DISF1.FOR	Subroutine used to display values assigned to variables by DF1.FOR.
DISF2.FOR	Subroutine used to display values assigned to variables by DF2.FOR.
DISF2.FOR	Subroutine used to display values assigned to variables by DF3.FOR.
REOX.FOR	Subroutine called by DWS4.FOR to perform calculations.
ENTRY.FOR	Subroutine used to convert a character string input into a numerical value for calculation and perform error checking of input for valid entries.
VALUE.FOR	A function used in character to numerical value conversion.

ERF.FOR	A function program used to evaluate the error function.
EXERFC.FOR	A subroutine to compute the complementary error function of y times an exponential with argument x.

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APPENDIX A

ADVECTION, DISPERSION AND CHEMICAL TRANSFORMATION IN STREAM

In this appendix procedures and formulas for estimating physical parameters of advection, dispersion and chemical transformation in surface water are presented.

A.1. ADVECTION

A compound introduced to a water body will be advected downstream with the bulk water at mean velocity U such that

$$U = Q/(B.d) \tag{A1}$$

where Q = stream flow, m^3/sec

For a given flow in a specific stream reach, width, depth, and velocity are related empirically by the following equations (Leopold and Maddock, 1953).

$$B = aQ^b \tag{A2a}$$

$$d = cQ^f \tag{A2b}$$

$$U = kQ^m \tag{A2c}$$

where the sum of the exponents (b+f+m) and the product of the constants (a.c.k) must equal 1.0. Although theoretical considerations predict that b = 0.23, f = 0.42, and m = 0.35, considerable variations have been observed among sites. Figure A.1 presents the exponents observed at 139 sites, as analyzed by Park (1977).

The upstream base flow for subwatersheds can be calculated from the relationship where:

$$Q_S^B = A_U \cdot q_s \tag{A3}$$

where q_s = average flow per unit area $\frac{m^3/sec}{m^2}$

Velocity at baseflow, U_o can be calculated by Manning's equation: (A4)

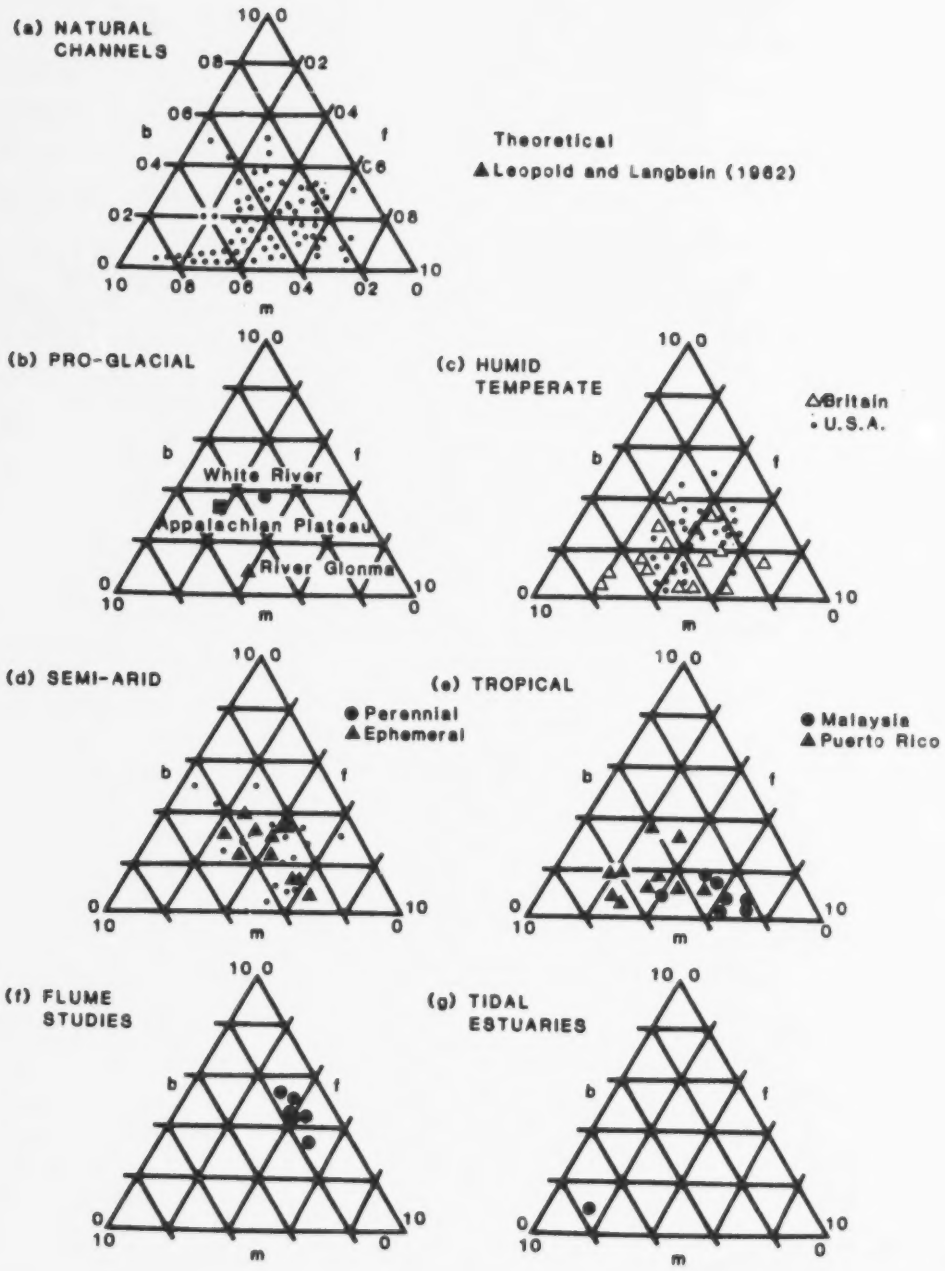

Figure A. Tri-axial graphs of at-a-station hydraulic geometry profiles.

$$U_o = d_o^{2/3} \cdot s^{1/2}/n$$

where: d_o = depth baseflow, m

s = channel slope, m/m

n = Manning's roughness coefficient, sec/m$^{1/3}$

The width at baseflow B_o, can be calculated from U_o, d_o, and the baseflow Q_S^B using equation A1 rearranged:

$$B_o = Q_S^B/(U_o \cdot d_o) \tag{A5}$$

The upstream flow during a storm includes both baseflow and runoff, as given by operation A6:

$$Q_U = Q_S^B + A_U \, P_{25} \, \overline{f}_R/100 \cdot t_s \tag{A6}$$

Given the baseflow values B_o, d_o, U_o, and Q_S^B and the stormflow value Q, the widths, depths, and velocities for stormflow conditions can be calculated as:

$$B = B_o \, (Q_U/Q_S^B)^b \tag{A7a}$$

$$d = d_o \, (Q_U/Q_S^B)^f \tag{A7b}$$

$$U = U_o \, (Q_U/Q_S^B)^{1-b-f} \tag{A7c}$$

When the theoretical values for b and f hold, U increases with Q to the 1/3 power. A ten-fold increase in flow, then, results in a doubling of velocity.

Streamflows and the associated hydraulic variables, then, can be synthesized from distributions of watershed areas A_s, areal flows q, channel slopes, s, channel roughness factors n, precipitation totals P_{25}, runoff coefficients f_R, and the hydraulic geometry exponents b and f.

A.2. DISPERSION

A compound advected through a water body will be mixed vertically, laterally, and longitudinally from areas of high concentration to areas of low concentration. The rate of mixing is proportional to the concentration gradient and either a turbulent mixing coefficient or a dispersion coefficient. A turbulent mixing coefficient in rivers is proportional to the length scaled and the intensity of turbulence, which is represented by the shear velocity:

$$U^* = \sqrt{g.d.s} \tag{A8}$$

where: U^* = shear velocity, m/sec

s = channel slope, m/m

d = mean depth, m

g = acceleration of gravity, m/sec^2

Because vertical mixing in streams occurs very quickly, we assume completion during the initial dilution stage. Lateral mixing is most important in the near field. It is smallest for uniform straight channels, and increases with curves and irregularities. Fischer et al. (1979) suggest calculating the lateral diffusion coefficient as:

$$E_y = 0.6 \cdot d \cdot U^* \quad , \pm 50\% \tag{A9}$$

The proportionality factor can vary evenly between 0.4 and 0.8.

Longitudinal turbulent mixing is generally much smaller than shear flow dispersion, which is caused by velocity gradients. Fischer and coworkers, suggest calculating the logitudinal dispersion coefficient with the approximate relationship:

$$E_x = 0.011\ U^2 \cdot B^2 / d \cdot U^* \tag{A10}$$

Here, again, the proportionality factor can vary $\pm$ 50%.

A.3. CHEMICAL TRANSFORMATION

A compound transported through a water body can undergo several physical and chemical transformations. Fast reactions are treated by assuming local equilibrium conditions. Sorption is considered to be in equilibrium with desorption:

$$S' + C_w = \overset{\Lambda}{C_s} \tag{A11}$$

where: S' = sediment concentration, kg/l

C_w = dissolved aqueous concentration, mg/l

$\overset{\Lambda}{C_s}$ = sorbed concentration, mg/l

The local equilibrium concentrations C_w and $\overset{\Lambda}{C_s}$ are governed by the equilibrium distribution coefficient K_p (ℓ/kg):

$$K_p = \frac{\overset{\Lambda}{C_s}}{S' \cdot C_w} \tag{A12}$$

Karickhoff et al., 1979, have shown that for sorption of hydrophobic organic compounds:

$$K_p = K_{oc} \cdot f_{oc} \qquad \text{(A13)}$$

where: K_{oc} = organic carbon partition coefficient, ℓ/kg

f_{oc} = organic carbon fraction of sediment

Karickhoff et al. (1979) further correlated K_{oc} with K_{ow} for organic sediments. Subsequent work by Karickhoff (1981) suggested the proportionality factor for mixed sediments of 0.4:

$$K_{oc} = 0.41 \cdot K_{ow} \qquad \text{(A14)}$$

Combining equations A12 - A14 and rearranging terms gives an expression for the fraction of the compound that is dissolved:

$$f_D = \frac{1}{1 + 0.41 \cdot K_{ow} \cdot f_{oc} \cdot S \cdot 10^{-6}} \qquad \text{(A15)}$$

The sorbed chemical fraction f_s is equal to $1 - f_D$.

The fraction of the compound that is dissolved in groundwater can be calculated from an equivalent expression:

$$f_{Dg} = \frac{\theta_g}{\theta_g + 0.41 \cdot K_{ow} \cdot f_{ocg} \cdot \rho_{bg}} \qquad \text{(A16)}$$

where: θ_g = volumetric water content of porous medium, ℓ^3/ℓ^3

f_{ocg} = organic carbon fraction of porous medium

ρ_{bg} = bulk density of porous medium, k_g/ℓ

and $$\rho_{bg} = 2.65 \cdot (1-\theta_g) \qquad \text{(A17)}$$

The sorbed chemical fraction f_{sg} is equal to $1 - f_{Dg}$.

Slower chemical transformation reactions can be treated generally by using mixed second order kinetics (Burns et al., 1982):

$$C_w + [E]_i \rightarrow P \qquad \text{(A18)}$$

where: $[E]_i$ = environmental property for process "i"

P = transformation product, mg/ℓ

The reaction rate R_i (mg/ℓ-sec) for process "i" is:

$$R_i = k_i \cdot Y_i \cdot f_D \cdot C \qquad \text{(A19)}$$

where: k_i = second order rate constant for process "i"

Y_i = yield coefficient for process "i"

C = total concentration of compound, mg/ℓ.

Given a local value for $[E]_i$, a pseudo-first order rate constant K_i (sec^{-1}) can be calculated:

$$K_i = k_i \cdot [E]_i \cdot Y_i \cdot f_D \qquad \text{(A20)}$$

For a compound undergoing several competing reactions, the overall pseudo-first order rate constant $K(sec^{-1})$ is

$$K = \sum_i K_i \qquad \text{(A21)}$$

This general second order reaction method can be used to predict reaction rates for photolysis, hydrolysis, oxidation, and bacterial degradation. For short reaches of rivers with travel times of hours, these reactions are not not likely to significantly reduce instream concentrations. For transient loads during storms, darkness should further reduce photolysis and, indirectly, oxidation. Bacterial communities are unlikely to acclimatize in hours to the transient loads. Of these transformation reactions, then, only hydrolysis will be considered for those few compounds with large rate constants. The nominal hydrolysis rate constant is calculated from the acid-catalyzed, neutral, and base-catalyzed pathways (Burns et al., 1982):

$$K_{Ho} = (k_{HA}[H^+]\ (\alpha . f_s + f_D) + k_{HN} + k_{HB}[OH^-]\ .(f_D))/3600. \qquad \text{(A22)}$$

where: k_{HA} = second-order acid-catalysis hydrolysis rate constant, ℓ/mole-hour

$[H^+]$ = hydrogen ion concentration = 10^{-pH}, mole/ℓ

pH = stream pH

α = acid-catalysis hydrolysis rate enhancement fractor for sorbed compound = 10

k_{HN} = neutral hydrolysis rate constant, sec^{-1}

k_{HB} = second-order base-catalysis hydrolysis rate constant, ℓ/mole-sec

$[OH^-]$ = hydronium ion concentration = 10^{-pOH}, mole/ℓ

pOH = stream pOH = 14 - pH.

For ground water, the nominal hydrolysis rate constant (in years^{-1}) is calculated from an equivalent expression:

$$K_{go} = (k_{HA}[H^+]_g(\alpha.f_{sg}+f_{Dg}) + k_{HN} + k_{HB}[OH^-]_g.f_{Dg}).(24).(365.25) \quad (A23)$$

where: $[H^+]_g$ = hydrogen ion concentration = 10^{-pHg}, mole/ℓ

pHg = ground water pH

$[OH^-]_g$ = hydronium ion concentration = 10^{-pOHg}, mole/ℓ

pOHg = ground water pOH = 14-pHg

The nominal hydrolysis rate constants K_{Ho} and K_{go} apply to a reference temperature, T_R (usually 25 °C). These can be corrected to ambient surface or ground water temperatures (T or T_g) with the following Arrhenius expressions.

$$K_H = K_{Ho} \cdot \exp[10^4 \cdot (\frac{1}{T_R+273} - \frac{1}{T+273})] \quad (A24)$$

$$K_g = K_{go} \cdot \exp[10^4 \cdot (\frac{1}{T_R+273} - \frac{1}{T_g+273})] \quad (A25)$$

A final transformation pathway to consider is volatilization. The volatilization rate constant K_v (sec^{-1}) can be calculated from the Whitman, or two-resistance model (Whitman, 1923; Burns et al., 1982):

$$K_v = \frac{1}{d} \cdot \frac{1}{R_L + R_G} \cdot f_D \quad (A26)$$

where: d = mean stream depth, m

R_L = liquid phase resistance, sec/m

R_G = gas phase resistance, sec/m.

The second term in equation A26 represents the conductivity of the compound through a liquid and a gas boundary layer at the water surface. The liquid phase resistance to the compound is assumed to be proportional to the transfer rate of oxygen, which is limited by the liquid phase only:

$$R_L = \frac{1}{K_{O2}.d.\sqrt{32/MW}} \quad (A27)$$

where: K_{02} = reaeration rate constant, sec^{-1}

MW = molecular weight of the compound

32 = molecular weight of oxygen.

The gas phase resistance to the compound is assumed to be proportional to the transfer rate of water vapor, which is limited by the gas phase only:

$$R_G = \frac{1}{\frac{H}{RT'} \cdot WAT \cdot \sqrt{18/MW}} \quad \text{(A28)}$$

where: WAT = water vapor exchange constant, m/sec

18 = molecular weight of water

H = Henry's law constant, atm-m^3/mole

R = ideal gas constant = 8.206 x 10^{-5} m^3-atm/mol °K

T' = water temperature (°K) = 273 + T.

The reaeration and water vapor exchange constants will vary with stream reach and time of year. They can be calculated using one of several empirical formulations. The water vapor exchange constant will be calculated using wind speed and a regression proposed by Liss (1973):

$$WAT = 5.16 \times 10^{-5} + 3.156 \times 10^{-3} \cdot W \quad \text{(A29)}$$

where: W = wind speed at 10 cm above surface, m/sec.

Wind speed measured above 10 cm can be adjusted to the 10 cm height assuming a logarithmic velocity profile and a roughness height of 1 mm (Israelsen and Hanson, 1962):

$$W = W_z \cdot \log (0.1/0.001)/\log (z/0.001) \quad \text{(A30)}$$

where: W_z = wind speed at height z (m/s)

Z = wind measurement height (m)

The reaeration rate constant will be calculated by the Covar method using stream velocity U and depth d, then corrected for temperature (Covar, 1976).

$$K_{02} = K_{20} \cdot 1.024^{T-20} \quad \text{(A31)}$$

where: K_{20} = reaeration rate at 20°C

For shallow streams where depth is less than 0.61 m, the Covar method uses the Owens formula:

$$K_{20} = 6.194.10^{-5} \cdot U^{0.67} \cdot d^{-1.85} \quad \text{(A32)}$$

For deeper, slower streams (d>0.61, U>0.518), the formula selected depends upon the transition depth:

$$K_{20} = 4.555 \cdot 10^{-5} \cdot U^{0.5} \cdot d^{-1.5} \quad \text{(A33)}$$

For deeper, faster streams (d>0.61, U>0.518), the formula selected depends upon the transition depth:

$$d_T = 4.1404 \cdot U^{2.9135} \quad \text{(A34)}$$

When $d>d_T>0.61$, the O'Connor-Dobbins formula is used. When $d_T>d>0.61$, the Churchill formula is used:

$$K_{20} = 5.825 \cdot 10^{-5} \cdot U^{0.969} \cdot d^{-1.673} \quad \text{(A35)}$$

In summary, three transformation processes are considered in this analysis: sorption, hydrolysis, and volatilization. Sorption of hydrophobic organic compounds is calculated by equation A15 using data for K_{ow}, f_{ow}, and s. Hydrolysis is calculated by equations A22 and A24 using data for pH, k_{HA}, k_{HN}, and k_{HB}. Volatilization is calculated by equations A26 through A30 using data for U, d, W, T, MW, and H. When insufficient data are available, conservative analyses can be completed ignoring any of these processes.

APPENDIX B

ANALYTICAL SOLUTION FOR TWO-DIMENSIONAL DUE TO PULSE LOADING

The stream transport model described in the main body of this report is based on our analytical solution for two-dimensional transport from a distributed vertical plane source in uniform flow (Figure B.1). The case involving pulse release of contaminant is considered. The analytical solution for this case is developed in this appendix.

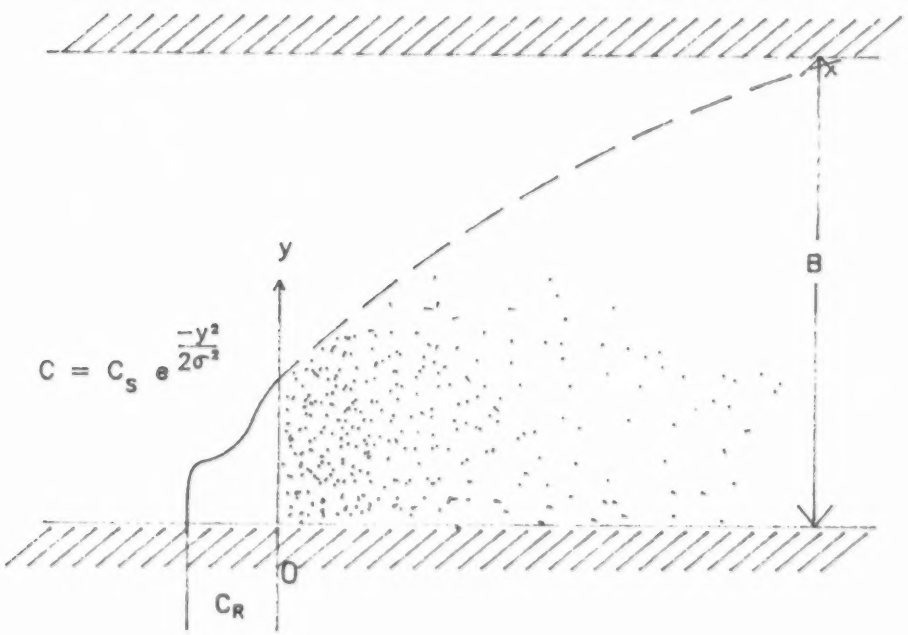

Figure B.1 Schematic description of two-dimensional transport in uniform flow in a stream of finite width, B.

Consider the region with the Gaussian distributed source shown in Figure B.1. The advective-dispersive equation for transport of a nonconservative contaminant in uniform stream flow can be written as:

$$U \frac{\partial c}{\partial x} - E_x \frac{\partial^2 c}{\partial x^2} - E_y \frac{\partial^2 c}{\partial y^2} + Kc + \frac{\partial c}{\partial t} = 0 \qquad (B1)$$

where E_x and E_y are dispersion coefficients in the logitudinal, x, and transverse, y, directions, respectively; U is the main flow velocity in the x-direction; c is the solute concentration; K is the first-order decay constant; and t is the elapsed time.

The initial and boundary conditions associated with equation B1 may be expressed as:

$$c\ (x,y,0) = 0 \qquad (B2)$$

$$c\ (\infty,y,t) = 0 \qquad (B3)$$

$$\frac{\partial c}{\partial y}\ (x,0,t) = 0 \qquad (B4)$$

$$\frac{\partial c}{\partial y}\ (x,B,t) = 0 \qquad (B5)$$

$$c\ (0,y,t) = C_s \exp\ (-y^2/2\sigma^2),\ t \leq t_R \qquad (B6)$$

$$c\ (0,y,t) = 0\ ,\ t > t_R$$

where C_s and σ are the peak concentration and standard deviation of the Gaussian source assumed to be located at x = 0.

The analytical solution for the above case can be derived in two steps. The first step involves an application of the image source theory to the fundamental solution of the corresponding case in which the stream is of infinite width and the contaminant is continuously released from the source. Let C_f^* denote the fundamental solutions. The expression for C_f^* has been derived in the report dealing with groundwater screening procedures. It may be written as:

$$C_f^*\ (x,y,t) = \left[\frac{\sigma x \exp\ (U_x/2E_x)}{(2\pi E_x)^{1/2}} \cdot I\right] C_s \qquad (B7)$$

where

$$I = \int_0^t \frac{\exp\left(-\frac{x^2}{4E_x\tau} - \frac{y^2}{4E_y\tau + 2\sigma^2} - \frac{U^2\tau}{4E_x} - K\tau\right) d\tau}{\tau^{3/2}\,(2\sigma^2+4E_y\tau)^{1/2}} \qquad \text{(B8)}$$

Image sources must be applied and their effects must be added to the fundamental solution to satisfy the zero normal gradient lateral boundary conditions. (Figure B.2 the actual source plus the first four image sources.) In general, an infinite number of image sources is required to reproduce the lateral boundary effect exactly. The resulting solution becomes:

$$C^*(c,y,t) = C_s\left[C_f^*(x,y,t) + \sum_{i=1}^{\infty} C_{fi}^*(x,y,t)\right] \qquad \text{(B9)}$$

where

$$C_{fi}^* = C_f^*(x,\ 2Bi + y\cos(i\pi),\ t) \qquad \text{(B10)}$$

The second step in the derivation involves an application of Duhamel's theorem of superposition in the time domain to satisfy the pulse source boundary condition (B6). Figure B.3 illustrates how the pulse load condition is obtained by superposing two continuous loads staggered over time interval t_R.

The combined response is the required analytical solution and is given by:

$$C_{x,y,t} = C_s\left[C_f^*(x,y,t) + \sum_{i=1}^{\infty} C_{fi}^*(x,y,t) - C_f^*(x,y,t-t_R) + \sum_{i=1}^{\infty} C_{fi}^*(x,y,t-t_R)\right] \qquad \text{(B11)}$$

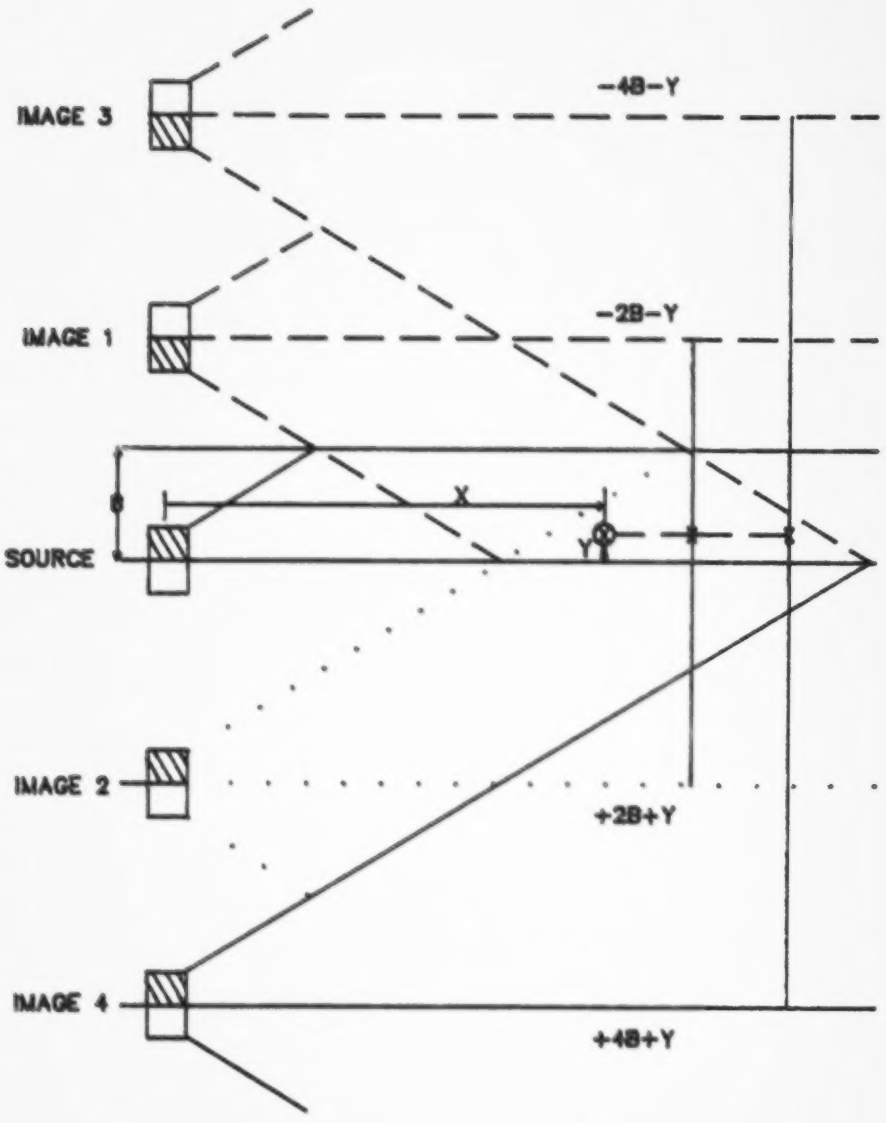

Figure B.2 Treatment of lateral boundary conditions using image sources.

APPENDIX C: LIST OF SYMBOLS

Text	Screen Input	Source Code	Screen Input	Definition
A_g				area of the contaminated catchment, m^2
A_S	A<S	AS		surface area of stream watershed above entry of leachate to stream, m^2
A_U	AU	AU		surface area of the watershed hydraulically above the contaminated catchment
A_W	A<W	AW		surface area of water disposal unit, m^2
b		B	B	initial plume width, m
b	b<exp	BEXP		width exponent for stream hydraulic geometry
B_0		BBO	BBO	stream width at baseflow, m
B		BB	BB	stream width during storm, m
C_{ADI}	C<ADI,	CADI	CCADI	acceptable daily intake concentration, mg/ℓ
C'_{ADI}	C'<ADI	CPADI		acceptable daily intake fish concentration, mg/kg
CCC	CCC	CCC		criterion continuous concentration to protect aquatic life, mg/ℓ
C_B				dissolved concentration in fish blood, mg/ℓ
C_D				maximum contaminant concentration in discharge, mg/ℓ
C_{DW}				concentration of dissolved contaminants in drinking water, mg/ℓ

Text	Screen Input	Source Code	Screen Output	Definition
$\overline{C}_{EXP}$				average stream concentration, mg/ℓ
C_F				average bioaccumulation concentration of dissolved contaminant in fish, mg/kg
C_f^*				fundamental solution for stream concentration, mg/ℓ
$\overline{C}_g$				average concentration across contaminated area of interception between ground water system and stream, mg/ℓ
C_I	C<I	CI		initial influent concentration, mg/ℓ
C_ℓ				lipid (fat) biomass concentration in fish tissues, mg/kg
C_L		CL	C<L	concentration of contaminant in leachate, mg/ℓ
$C_{n\ell}$				non-lipid (blood, muscle) biomass concentration in fish tissues, mg/kg
C_R				concentration of contaminant in the surface runoff, mg/ℓ
$\overline{C}_{s,D}$				average concentration in stream for direct discharge situation, mg/ℓ
C_0				average concentration of contaminant in the mixing zone adjacent to the stream entry point, mg/ℓ
C_x				concentration at distance x downstream from the stream entry point, mg/ℓ
$\overline{C}_x$				contaminant concentration for ground water loading, mg/ℓ
$C_{x,y}$				contaminant concentration, mg/ℓ
$\overline{C}_{x,y}$				average concentration for direct discharge, mg/ℓ

Text	Screen Input	Source Code	Screen Output	Definition
$C_{0,y}$				Contaminant concentration distribution across the mixing zone, mg/ℓ
D		DD	DD	stream dilution factor
d		D		mean stream depth, m
D'		DDP	D'	combined ground water and surface water dilution factor, A_2/A_s
DF		DF		ultimate dilution after complete mixing in the stream
d_0	d<0		DO	mean stream depth at base flow, m
E_x		EX	EX	longitudinal dispersion coefficient, m^2/sec
E_y		EY	EY	lateral dispersion coefficient, m^2/sec
f	f<exp	FEXP		depth exponent for stream hydraulic geometry
f_D		FD	f<D	fraction of contaminant that is dissolved
f_{Dg}				fraction of compound that is dissolved
fℓ	f<l	FL		fraction of fish biomass that is lipid
f_{oc}	f<oc	FOC		organic carbon fraction of suspended sediment
f_{ocg}	FOCG	FOCG		organic carbon fraction of aquifer medium
$\overline{f}_R$	R<S	RS		average monthly and regional runoff coefficient
f_R	R<W	RW		waste site runoff coefficient
f_R^*		FR		stream flow recession parameter
f_S		FS	FS	fraction of chemical that is sorbed

Text	Screen Input	Source Code	Screen Output	Definition
g		G		acceleration of gravity, 9.81 m/sec^2
H	H	H		Henry's law constant, atm-m^3/mole
$[H^+]$		H		hydrogen ion concentration = 10^{-pH} mole/ℓ
K		KK	KK	surface water decay rate constant, sec^{-1}
k_{HA}	k<HA	KHA		second-order acid-catalysis hydrolysis rate constant, ℓ/mole-hour
k_{HB}	k<HB	KHB		second-order base-catalysis hydrolysis rate constant, ℓ/mole-hour
k_{HN}	k<HN	KHN		neutral hydrolysis rate constant, hour^{-1}
K_F		KF	K<F	fish partition coefficient (bioaccumulation), ℓ/kg
K_g				total effective decay constant in ground water, years^{-1}
K_H		KH	KH	Pseudo first order rate constant for hydrolysis, sec^{-1}
Kℓ				lipid fish tissue partition coefficient, ℓ/kg
$K_{n\ell}$				non-lipid fish tissue partition coefficient, ℓ/kg
K_{oc}	K<OC	KOC		organic carbon partition coefficient, ℓ/kg
K_{ow}	K<OW	KOW		octanol-water partition coefficient, ℓ_{oct}/ℓ_{water}
K_v		KV	KV	pseudo first order volatilization rate constant, sec^{-1}
$\dot{m}_D$				effluent contaminant mass flux, g/sec
$\dot{m}_g$				ground water contaminant mass flux, g/sec

Text	Screen Input	Source Code	Screen Output	Definition
$\dot{m}_L$				contaminant mass flux leaching from land disposal unit, g/sec
$\dot{m}_R$				runoff mass flux, g/sec
$\dot{m}_w$				industrial waste mass flux, g/sec
MW	MW	MW		molecular weight of compound
n	N	N		Manning roughness coefficient, $sec/m^{1/3}$
pH	pH	PH		stream pH
pHg	PHG	PHG		ground water pH
pOH		POH	POH	stream pOH
pOH_g		POHG		ground water pOH
$\overline{P}$				average annual precipitation, m
P_{25}	P<25	P25		average precipitation for 25-year, 24-hour storm, m
q	q	Q		average stream flow per unit area, $m^3/sec/m^2$
Q		QQ	QQ	stream flow for storm conditions, m^3/sec
Q_D	Q<D	QD		wastewater discharge, m^3/sec
Q_g				contaminated ground water discharge, m^3/sec
Q_L				rate of percolation through the land disposal, m^3/sec
Q_R		QW	QW	storm runoff flow, m^3/sec
Q_S		QQ		total downstream flow, m^3/sec
Q_S^B		QQO	QQO	stream base flow before storm, m^3/sec
Q_{SR}		QSR		runoff flow to stream from catchment containing facility, m^3/sec

Text	Screen Input	Source Code	Screen Output	Definition
Q_w	Q<W	QWI	Q<W	industrial waste flow, m^3/sec
Q_U		QU	QU	stream base flow plus upstream storm runof, m^3/sec
R_G		RG		gas phase resistance, sec/m
R_L		RL	RL	liquid phase resistance, sec/m
s	s	S		channel slope, m/m
S	S	SS		sediment concentration, mg/ℓ
S'		SS		sediment concentration, kg/ℓ
t_L	t<L	TL		time of total runoff or ground water loading, sec
t_{DP}				time of loading for pulse discharge, sec
t_{Ds}				time of loading for continuous discharge, sec
T_G	TG	TG		temperature of the ground water, °C
t_R		TR	TR	time duration of the contaminant loading, sec
T	T	T		water temperature, °C
T'		TK	TK	water temperature, °K = 273 + T
T_{rg}	TRG	TRG		reference temperature, temperature at which hydrolysis rate constant, was measured in the laboratory (usually 20-25°C), °C
t_{RP}	T<RP	TRP		time of loading for pulse runoff, sec
t_{RS}	T<RS	TRS		time of loading for steady runoff, sec
T_{SD}		TSD	TSD	time in which the stream reaches maximum concentration at a distance x, sec

Text	Screen Input	Source Code	Screen Output	Definition
U		U	U	stream velocity during storm, m/sec
U_0		U0	U0	stream velocity at base flow, m/sec
U*		USV	USV	stream shear velocity, m/sec
V_g	VWG	VWG		ground water seepage velocity, m/year
W	W	W10	W10	wind speed at 10 cm above surface, m/sec
WAT		WAT	WAT	water vapor exchange constant, m/sec
x		X	X	downstream (longitudinal) distance from discharge, m
X_g	XG	XG		distance from land disposal site to stream, m
Y_i				yield coefficient for process "i"
y		Y1	Y	lateral distance from discharge, m
α		ALPHA	ALPHA	acid-catalysis hydrolysis rate enhancement factor for sorbed compound
β		BETA	BETA	kinetic reduction exponent = k . x/U
ζ_{EXP}				aquatic exposure factor
ζ_D		RD	R<D	reduction factor for direct discharge (dilution plus reaction)
ζ_{DW}				drinking water treatment dilution factor
ζ_F				bioaccumulation factor in fish, ℓ/kg
ζ_g		RG	RG	ground water dilution factor
ζ_H				ground water attenuation factor accounting for effects of hydrolysis in the aquifer
ζ_T				attenuation factor for transport in the stream (ground water loading)

Text	Screen Input	Source Code	Screen Output	Definition
ζ_w		RW	R<W	treatment plant attenuation factor due to sorption and settling, volatilization, and bacterial degradation
σ		SIGMA	SIGMA	standard deviation of Gaussian source, m
σ_D				standard deviation of Gaussian source for direct discharge
σ_R				standard deviation of Gaussian source for storm runoff
τ_g		TAUG	TAUG	time taken by the contaminant to travel from the land disposal unit to the stream entry point, years
θ_g	THETAG	THETAG		ground porosity

APPENDIX D

SAMPLE OUTPUTS

Sample Output:

D.1 Scenario 1B (Ground Water/Fish Consumption), Default Values #1

SARAH Model Scenario IC

Scenario 1 Steady Ground Water Loading Run Program

```
KHG(/YR) = 0.00000E + 00
  TAUG   = 0.17797E + 03
    RG   = 0.10000E + 01


    D'   = 0.10000E + 00
   C<L   = 0.10000E + 02
```

Sample Output:

D.2 Scenario 1C (Ground Water/Aquatic Toxicity), Default Values #1

SARAH Model Scenario IB

Scenario 1 Steady Ground Water Loading Run Program

```
KHG(/YR) = 0.00000E + 00
  TAUG   = 0.17797E + 03
    RG   = 0.10000E + 01


    D'   = 0.10000E + 00
   f<D   = 0.99980E + 00
   K<F   = 0.31000E + 03
   C<L   = 0.32265E - 01
```

Sample Output:

D.3 Scenario 2A (Steady Storm/Drinking Water), Default Values #1, Gaussian Solution

Drinking Water Model

Scenario 2A Storm Runoff Loading Run Program

```
QQ0    = 0.50000E - 01
QQ     = 0.59817E + 01
D0     = 0.30000E + 00
D      = 0.22378E + 01
BB0    = 0.15687E + 01
BB     = 0.47147E + 01
U0     = 0.10624E + 00
U      = 0.56696E + 00

QW     = 0.72338E + 00
DF     = 0.12093E + 00
DD     = 0.10000E + 01
B      = 0.57016E + 00
SIGMA  = 0.45492E + 00

USV    = 0.44449E - 01
EY     = 0.59681E - 01
EX     = 0.79016E - 00

FD     = 0.99980E + 00
POH    = 0.70000E + 01
ALPHA  = 0.10000E + 02
FS     = 0.20496E - 03
KH     = 0.00000E + 00
W10    = 0.10000E + 01
WAT    = 0.32076E - 02
TK     = 0.29300E + 03
RG     = 0.55871E + 09
RL     = 0.24382E + 06
KV     = 0.79932E - 09
KK     = 0.79932E - 09
```

Sample Output:

D.4 Scenario 3A (Catastrophic Runoff Loading/Drinking Water), Default Values #1, Gaussian Solution

Drinking Water Model

Scenario 3A Catastrophic Pulse Loading Run Program

```
QQ0   = 0.50000E - 01
QQ    = 0.11856E + 02
D0    = 0.30000E + 00
D     = 0.29826E + 01
BB0   = 0.15687E + 01
BB    = 0.55181E + 01
U0    = 0.10624E + 00
U     = 0.72033E + 00

QW    = 0.86806E + 01
DF    = 0.73219E + 00
DD    = 0.10000E + 01
B     = 0.40403E + 01
SIGMA = 0.32237E + 01

USV   = 0.51316E - 01
EY    = 0.91835E - 01
EX    = 0.11355E - 01

FD    = 0.99980E + 00
POH   = 0.70000E + 01
ALPHA = 0.10000E + 02
FS    = 0.20496E - 03
KH    = 0.00000E + 00
W10   = 0.10000E + 01
WAT   = 0.32076E - 02
TK    = 0.29300E + 03
RG    = 0.55871E + 09
RL    = 0.24973E + 06
KV    = 0.59970E - 09
KK    = 0.59970E - 09
```

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